SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT
Final Report
FHWA/IN/JHRP-90/10

THE EFFECTS OF BAG HOUSE FINES AND INCOMPLETE COMBUSTION PRODUCTS IN A DRUM DRIER ON THE CHARACTERISTICS OF ASPHALT PAVING MIXTURES - PHASE II

J. D. Lin

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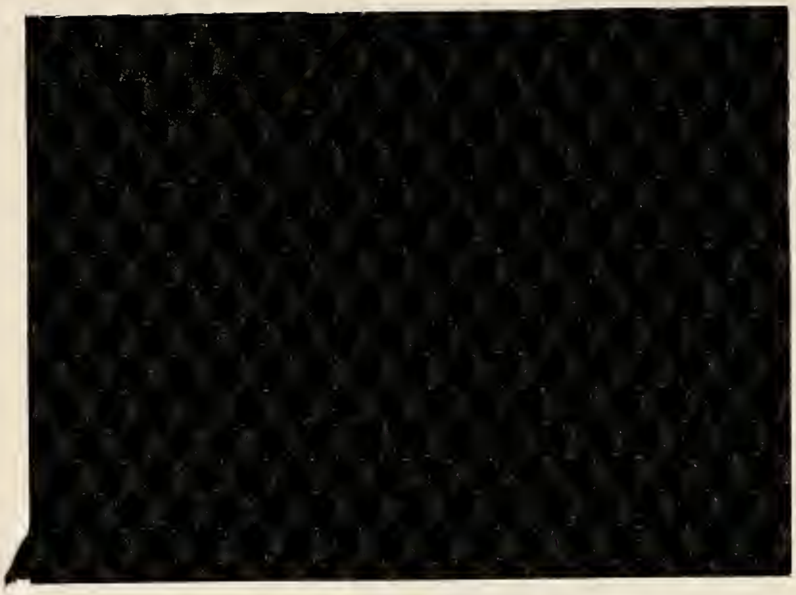

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Final Report

The Effects of Bag House Fines and Incomplete Combustion Products in a Drum Drier on the Characteristics of Asphalt Paving Mixtures - Phase II

To:	Harold L. Michael Joint Highway Research Project	August 22, 1990 Project: C-36-6II
From:	Leonard E. Wood Research Engineer	File: 2-4-36

This letter will serve to transmit the Final Report titled "The Effects of Bag House Fines and Incomplete Combustion Products in a Drum Drier on the Characteristics of Asphalt Paving Mixtures - Phase II". It was prepared by J. D. Lin and L. E. Wood and represents the work of J. D. Lin of our staff.

This report concentrates on the effects of bag house fines on characteristics of asphalt paving mixtures and contains 10 chapters. Chapter 1 presents a general overview of the project and its objectives. Chapter 2 presents a brief literature review of pertinent technical articles dealing with bag house fines. Chapter 3 describes the materials and the equipment used in the study. Chapter 4 details the laboratory procedures followed in the study. Chapter 5 outlines the experimental design of the study. Chapter 6 covers the influence of bag house fines on asphalt mastics. Chapter 7 presents the influence of various bag house fines on asphalt paving mixtures. The effects of bag house fines on the ability of asphalt paving mixtures to resist aging, moisture and densification is covered in Chapter 8. Chapter 9 examines the influence of particle size of the bag house fines on asphalt paving mixtures. A summation of the study is presented in Chapter 10.

This report is presented for review and approval as evidence of fulfillment of the objectives of this project.

Respectfully,

Leonard E Wood

Leonard E. Wood
Research Engineer

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by

J. D. Lin

Joint Highway Research Project

Project No.: C-36-6II
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Prepared for an Investigation
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16. Abstract An extensive laboratory study of the asphalt paving mixtures containing baghouse fines has been conducted through seven sets of experimental designs to characterize the performance of pavement. Marshall size specimens of asphalt paving mixtures with different kinds and amounts of baghouse fines were fabricated using the gyratory testing machine. The following techniques were used to evaluate the influence of the various variables upon mechanical properties such as: gyratory parameters, resilient modulus, indirect tensile strength, indirect creep, and Hveem stability tests to evaluate their mechanical properties. In addition, in the asphalt paving mixtures, asphalt cement was replaced with baghouse fines in order to maintain a constant volume of asphalt cement plus baghouse fines. The evaluation was conducted under the simulation of plant aging, environmental aging, moisture damage, and traffic densification.

The gyratory stability index and gyratory elasto-plastic index can be used to determine the effect of baghouse fines on asphalt paving mixtures during specimen fabrication. The resilient modulus, indirect tensile strength, and Hveem stability decrease significantly with higher amounts of baghouse fines. Artificial aging processes to simulate pavement performance caused an increase in resilient modulus and the indirect tensile strength as well as a reduction in failure tensile strain. The effect of water sensitivity of asphalt paving mixture decreased with increasing amount of asphalt cement or with decreasing of baghouse fines/asphalt cement ratio. Densification of asphalt paving mixtures produces higher indirect tensile strength, but it also decreased the resilient modulus. The resilient modulus value was insensitive to the gradation of baghouse fines or mineral fillers, but the indirect tensile strength increased significantly with finer fines or fillers.

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ABSTRACT

Asphalt paving mixtures that are to be utilized in paving structures must have properties that will prevent or minimize the following primary distress modes: (1) thermal or shrinkage cracking, (2) fatigue cracking, (3) permanent deformation or rutting, (4) moisture sensitivity. An extensive laboratory study of the asphalt paving mixtures containing baghouse fines has been conducted through eleven sets of experimental designs to characterize the performance of pavement. Marshall size specimens of asphalt paving mixtures with different kinds and amounts of baghouse fines were fabricated using the gyratory testing machine. The following techniques were used to evaluate the influence of the various variables upon mechanical properties, gyratory parameters, resilient modulus, indirect tensile strength, indirect creep, and Hveem stability tests. In addition, in the asphalt paving mixtures, asphalt cement was replaced with baghouse fines in order to maintain a constant volume of asphalt cement plus baghouse fines. The evaluation was conducted under the simulation of plant aging, environmental aging, moisture damage, and traffic densification.

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The results of this study will provide the highway engineer with a better understanding of the effect of different factors on the mechanical properties of hot asphalt paving mixtures with baghouse fines.

CHAPTER 1

INTRODUCTION

1.1 Background

The Clean Air Act of 1970 was established by Environmental Protection Agency. In 1973 the Environmental Protection Agency issued strict air pollution control codes and standards for the emission of particles from the asphalt plants into the atmosphere. All new plants purchased after June, 1973 are limited to 0.04 gm of particles per cubic foot of exhaust gas (1).

This strict regulation has forced contractors to equip their plants with a baghouse as either a primary or secondary dust collector (2), or as a replacement of wet scrubber. Baghouses have been installed instead of wet scrubber systems for primarily economic reasons. In contrast to wet scrubbers the baghouse is easier to maintain. It does not need water. It does not have any problem concerned with the disposal of a water slurry. To offset the cost of the baghouse and the associated dust disposal problems, many plants are adding the collected dust to asphalt paving mixtures. This feedback of collected dust to mixtures has led to a considerable debate (3).

The reuse of baghouse fines has been associated by different investigators with poor compaction, bleeding and flushing, and tender mixes. Those baghouse fines are often much finer than the traditional mineral fillers that have been used in the past years. Unfortunately, the research on the characteristics of baghouse fines has not been sufficient. As a result a number of highway agencies have been concerned as to the proper handling and use of baghouse fines. Thus, it is worthwhile to investigate and evaluate the effects of baghouse fines on asphalt paving mixtures.

1.2 Problem Statement

The Indiana Department of Transportation has experienced early distresses in some asphalt pavement sections. The increased use of drum mixers and the resulting incorporation of baghouse fines in asphalt paving mixtures has caused a question to be raised concerning the influence of those baghouse fines upon the behavior of asphalt paving mixtures. The baghouse fines can serve either as binder extender or stiffener depending on their characteristics. There is a need to better understand the role of such baghouse fines.

An investigation of all possible asphalt pavements in which baghouse fines have been incorporated would necessarily entail a research effort that is widespread and time consuming. Therefore, it is the intention of this study to conduct a laboratory investigation to evaluate the effects of baghouse fines in laboratory to evaluate their mechanical properties and performance of asphalt paving mixtures.

There are several unanswered questions in the area of asphalt paving mixtures with baghouse fines; a long term aging and water damage, a long term effect of traffic densification, stability and compactibility, and the interaction between asphalt and baghouse fines. There is a need for assurance that those effects would not be harmful.

1.3 Object of the Study

The object of this study is to characterize typical baghouse fines which are found in Indiana and to determine their influence on the behavior of asphalt paving mixtures. This would be accomplished by concentrating in the following areas:

1. Mineralogical Characterization and grain size analysis of typical baghouse fines found in Indiana.
2. Physical tests on asphalt mastics that have different amounts of various baghouse fines.
3. Mechanical tests on asphalt paving mixtures that have different amounts of various baghouse fines and asphalt cement.
4. Evaluation of the effect of weathering by means of artificial laboratory conditioning on asphalt paving mixtures with baghouse fines.

The mechanical properties are determined by means of resilient modulus, indirect tensile strength test, indirect creep tests, and Hveem stability test.

1.4 Organization of this Study

This study contains ten chapters. Chapter 2 is the literature review of work included on the area of mineral fillers and baghouse fines. It also contains some theoretical background for several tests that were used to determine major mechanical properties evaluated in this study. Chapter 3 contains a description of the materials and equipment. Chapter 4 describes the test procedures employed in this study. Chapter 5 contains an outline of the experimental designs conducted in this study. Chapter 6 presents the research work conducted to evaluate and characterize the asphalt mastics. Chapters 7 and 8 present the evaluation and characterization of the asphalt paving mixtures with different amount of baghouse fines under long term performance and densification. Chapter 9 contains the comparison between baghouse fines and mineral fillers. Chapter 10 contains the summary and conclusions and the recommendation for further research respectively.

1.5 Implementation

Implementation of the results of this study could lead to a better utilization of baghouse fines in the Indiana Department of Transportation asphalt paving mixtures. The end result would increase the service life and lower maintenance costs of asphalt pavements in Indiana.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

According to ASTM standard specification D242 (4), the definition of mineral filler is finely divided mineral matter such as rock dust, slag dust, hydrated lime hydraulic cement, fly ash, loess or other suitable mineral matter. At the time of use it shall be sufficiently dry to flow freely and essentially free from agglomerations. A great deal of research has been conducted on mineral filler and its effect on asphalt paving mixtures. Baghouse fines can also be considered as a mineral filler, however, because they are a rather recent development relatively little research has been done on them. They differ from the more traditionally used mineral fillers in that they can contain a much larger percentage of very fine (< 10 μm) particles.

2.2 Baghouse Fines

Scrimsher (5) examined the effect of different baghouse fines on Hveem mix design parameters. He found that using a maximum of 2% baghouse fines content has little effect on Hveem stability. When an extremely fine mineral dust is added to an asphalt mixture as a filler to correct a deficiency in the aggregate gradation, a reduction in the asphalt content is necessary to prevent asphalt pavement flushing and instability. He recommended that the contractors should be permitted to introduce as much as 2% baghouse fines into the weigh box at the pugmill. The report also recommended that the actual baghouse fines used in the laboratory mixture design can be used in asphalt paving mixtures in the field.

Erick and Shook (6) conducted a study on baghouse fines in 1976 and 1977. They analyzed the properties of several typical baghouse fines, fine-asphalt mixtures, and asphalt-aggregate-fines mixtures. They compared these properties to known properties of commercial mineral fillers and filler-asphalt mixtures and determined to what extent the reintroduction of baghouse fines affects asphalt mastic properties, asphalt mixture properties and asphalt pavement performance. They concluded that baghouse fines were satisfactory for use in the mix as long as the quality of the parent aggregate is satisfactory.

Ward and McDougal (7) studied baghouse fines from 16 sources with a wide variety of particle size distribution, mineralogical composition, and other physical properties. Three different types of baghouse fines with varying degrees of fineness were studied to evaluate the influence upon the Hveem stability and dynamic modulus. The baghouse fines, a particle size less than 20 μm, tended to combine with asphalt cement and act as an asphalt extender. The report concluded that when baghouse fines were used in proper quantities, it was not harmful to the paving mix. Baghouse fines could serve as an inexpensive and beneficial substitute for part of the asphalt cement to decrease the cost of asphalt pavement.

Dukatz and Anderson (8) studied the influence of baghouse fines and cyclone fines on the properties of Marshall samples. It was found that flow and stability were relatively insensitive to source of the filler or the asphalt, but that the creep compliance of the samples was affected by the filler and the source of the asphalt. They also attempted to relate mixture compactibility to the stiffness of the filler-asphalt mixtures and found a limited correlation, indicating that the stiffer filler-asphalt mixtures reduce mixture compactibility.

Gietz (9) using the Rolling Thin Film Oven studied the viscosity of baghouse fines-asphalt mixtures. There was a significant variation in the behavior of different fines after aging in the RTFO test. Temperature susceptibility and hardening were different for the different baghouse fines and for the two different asphalt cements. There was a strong interaction between the fines and the asphalt cement.

Kandhal (10) examined eight baghouse fines from the primary collector. He verified Rigden's (13) earlier relationships between stiffening of filler/asphalt mixtures and the void characteristics of the dry-compacted dust. From the study Kandhal developed some specification criteria for baghouse fines. The bulk volume of the fines to asphalt cement in a mixture should be less than 50%, if the bulk volume is greater than 50%, a check on softening point must be performed. If the bulk volume of the fines is greater than 50%, the maximum allowable increase in softening point is less than 11°C. The percentage of retained tensile strength, based on the Idaho Moisture Sensitivity Test should be greater than 50%. He found no satisfactory relationship between the consistency of the filler-asphalt mixtures and size distribution, particle shape, surface area, plasticity index, or mineralogical composition of the baghouse fines.

Maupin (11) conducted a study on the effect of baghouse fines on mixture voids, stability, and penetration time. He found that increases in baghouse fines content produced large changes in mixture behavior and design properties.

Anderson and Tarris (12,1) studied the addition of dust collector fines to asphalt paving mixtures. Thirty-three different baghouse fines were sampled in order to establish the day to day and within day variability of baghouse fines. The variability of gradation was largely related to efficiency of the primary collector. Without a primary dust collector, baghouse fines can be very coarse, ranging up to the No. 30 sieve mesh with as little as 20-30% passing No. 200 mesh. They also discussed a considerable variety of collection equipment and practices. In another study (14,15) different proportions of primary and secondary dusts were added to mixtures and the Marshall properties were measured. The fineness of the dust was not a good predictor of the stiffening effect of the dust, although the finer dusts did produce appreciable stiffening. The baghouse fines that significantly stiffened the mixtures affected the air voids and reduced the compactibility of the mixtures. The finer dusts also acted as asphalt extenders and reduced the air voids. Filler/asphalt ratio might be a better control criteria than merely setting an upper limit on the percentage of baghouse fines. When baghouse fines were used as an asphalt extender the mix properties could be very sensitive to change in asphalt content. When baghouse fines were added at a plant, or when baghouse fines were introduced to an existing design, a complete mixture design, including a voids analysis, should be performed.

Anani and Al-Abdul-Wabhab (16) analyzed the Marshall tests on asphalt paving mixtures that had various ratios of filler to baghouse fines. The results of this study indicated that baghouse fines could greatly affect the properties of the mixture, such as increased optimum asphalt content, increased mixture stability, and decreased resistance of the mixture to water damage. One factor that controls the effect of baghouse fines on asphalt mixture was the percentage of carbon. The larger percentage of carbon in the baghouse fines would decrease the stability loss of the mixture and increase the optimum asphalt content.

Kriech (17) studied factors which influence Type IV sand mix performance. The report concluded that baghouse fines were a major contributor to reduction of permeability in sand mixture which results in lower skid numbers. The level of baghouse fines in the asphalt film played the important roles. First it swells the asphalt film larger by acting as an extender. This lowers the volume of air voids and significantly reduced the number of interconnected voids. Secondly, the baghouse fines stiffen the asphalt changing its rheological properties and making it more difficult to achieve proper mixture density.

Anderson (18,19,20) used Marshall compaction to form specimens which were tested for indirect resilient modulus, creep, and strength. Additional specimens were made using a kneading compactor. These specimens were tested for compressive creep and dynamic modulus. The mechanical properties of the mixes were then compared with the stiffness of the dust-asphalt mixtures and to the physical properties of the dust to determine the effect of different dust-asphalt ratios and dust sources on the properties of hot asphalt paving mixtures. Anderson concluded that maximum filler-asphalt cement ratio of 1.2 to 1.5 based upon weight should be recommended. The 1.2 ratio had been used successfully in laboratory and field experiments, and this may be tentatively increased to 1.5 based upon the results of this study. The fillers, baghouse fines, or other fines that were used for mixture design must be the same as those that were used for producing the mixture at the asphalt paving facility. Legislative attempts to dispose of large quantities of various fines, such as fly ash, into asphalt paving mixtures should be carefully evaluated in laboratory experiments and field trials. The stiffening effect of baghouse fines on asphalt mixtures could be effectively measured during mixture design through viscosity, penetration, softening point, bulk density for dry compacted dust, or kerosene absorptivity testing. Based upon the current state of the art, there was nothing to suggest that filler or baghouse fines levels that produce stiffening ratios greater than 10 to 15 were harmful to asphalt pavement construction or road performance. Baghouse fines or fillers that produce very large stiffening ratios may, however, lead to brittle mixes or mixes that are hard to compact.

In summary, the review of the literature on baghouse fines indicates:

(1) The size of the dust collected from baghouse collection systems depends on the pavement aggregate, the plant configuration, and the operating condition at the plant.

(2) When possible, the mix design should be incorporate the same baghouse fines that will be used in the actual mixture.

(3) The behavior of baghouse fines in asphalt paving mixtures cannot be predicted on basis of fineness alone. Additional testing of the baghouse fines is required in order to predict its behavior.

(4) Baghouse fines can be act as an asphalt extender, but it can also interact with asphalt cement and stiffen the asphalt mastics.

CHAPTER 3

MATERIALS AND EQUIPMENT

3.1 Materials

3.1.1 Baghouse Fines

Thirty different samples of baghouse fines were collected from asphalt plants by INDOT personnel. Figure 3.1 given is the location of asphalt plants. These baghouse fines represent different generic types depending on the aggregate processed. The characteristics of those baghouse fines are reported in Chapter 6.

3.1.2 Mineral Fillers

Four different kinds of mineral fillers were collected from cement concrete and bituminous laboratory at Purdue University. They represent a wide range of chemical and physical properties of mineral fillers available. The single Class C fly ash is an excellent fly ash and is utilized widely in Indiana portland cement concrete. It was collected from the Rockport Station of the Indiana and Michigan Electric Co. Microsilica EMS 900 silica fume supplied by Elkem Chemicals Inc., Pittsburgh, PA, was used in this study. The data provided by supplier show that this product contains mainly amorphous SiO_2 and carbon. The content of amorphous SiO_2 is stated about 95% by weight. The particle sizes of silica fume are nearly all less than 5 μm. It has a bulk density about 0.125 g/cm^3 and specific gravity of 2.2. Hydrated

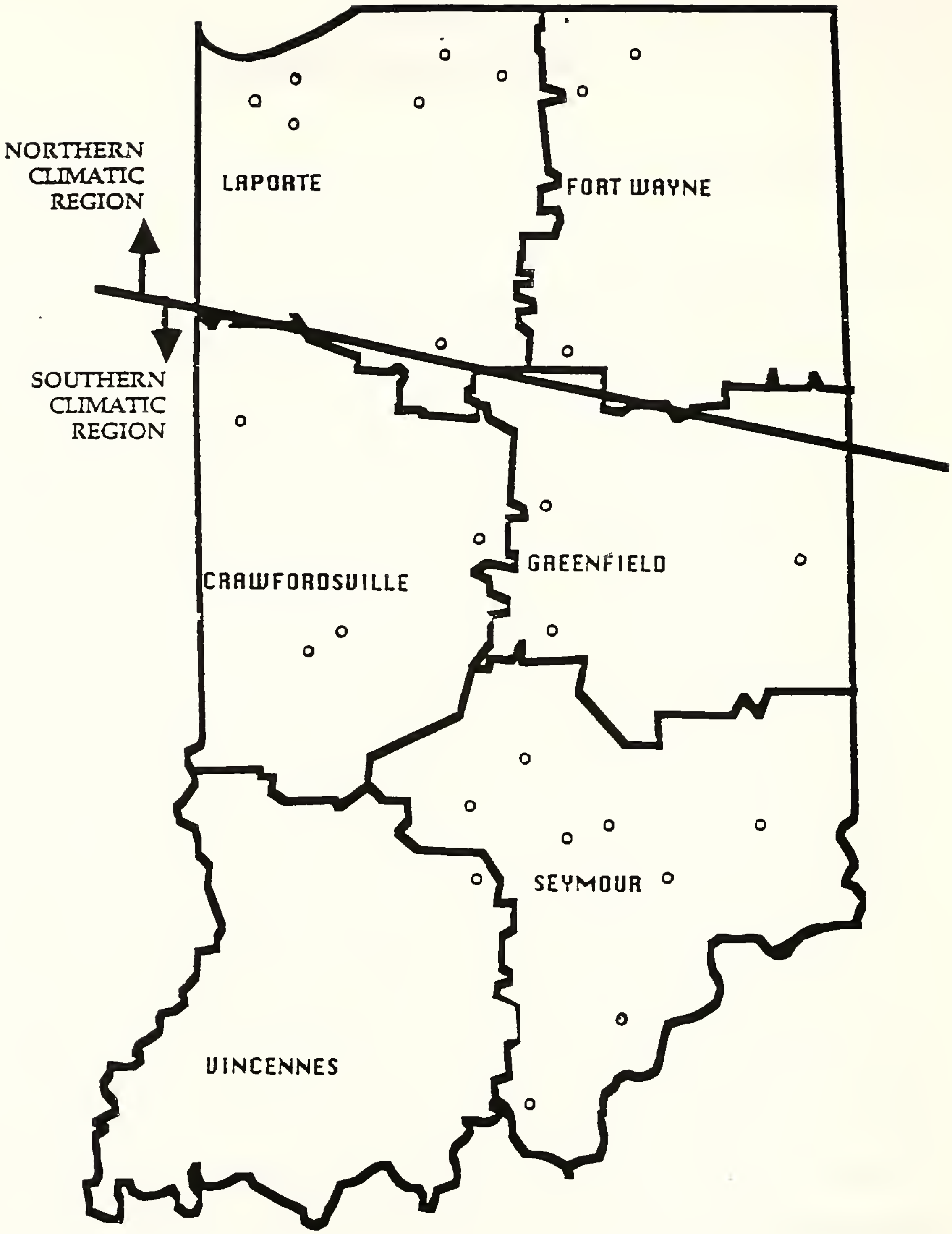


Figure 3.1 The Location of Baghouse Fines

lime is commercially used for mineral filler in asphalt plants. The main component is $Ca(OH)_2$, it has a bulk density about 1.29 g/cm^3, specific gravity of 2.72. Silica rock flour is also commercially used as a mineral filler in asphalt plants. The main component is SiO_2. It has bulk density about 1.67 g/cm^3, specific gravity of 2.76. Table 3.1 shows the chemical and physical properties of fly ash.

3.1.3 Aggregate

The aggregate used in the study was a limestone obtained from the Erie Stone Company of Huntington, Indiana. The aggregate has been stored in the Purdue Bituminous Laboratory and has been used by many researchers. Its physical properties are shown in Table 3.2. Figure 3.2 presents the gradation of the limestone used in the asphalt mixture design. Table 3.3 gives the gradation of the asphalt paving mixtures used corresponding to each baghouse fines content. The job-mix formula meets all the requirements of the ASTM Standard Specification D3515 (21,22). Adjusting gradation by the baghouse fines or mineral filler content is based on adjusting formula suggested by Asphalt Institute MS-2 (22) or Caltrans (23).

3.1.4 Asphalt Cement

The three grades of asphalt cement were used in this study: an AC-5, AC-10, and AC-20. The asphalt cement was supplied by Amoco, Whiting, Indiana. Their physical properties are shown in Table 3.4.

Table 3.1 Chemical and Physical Properties of the Fly Ash

SiO_2 (%)	35.8
Al_2O_3 (%)	19.6
Fe_2O_3 (%)	6.4
$SiO_2+Al_2O_3+Fe_2O_3$ (%)	61.8
CaO (%)	26.8
MgO (%)	3.3
Loss of Ignition (%)	0.34
Specific Gravity	2.61
Mean Size μm	14
% > 45 μm	21

Table 3.2 Results of Tests on Aggregates

Size	Material	Bulk Specific Gravity*	Apparent Specific Gravity*	Absorption (%)
1/2"-3/4"	Limestone	2.678	2.730	0.8
3/8"-1/2"	Limestone	2.700	2.767	1.2
#4 -3/8"	Limestone	2.643	2.765	2.1
#4 -#8	Limestone	2.666	2.702	1.8
#8 -#30	Natural Sand	2.698	2.733	0.8
#30 -#50	Outwash Sand	2.607	2.707	1.2
#50 -#200	Natural Sand	2.644	2.710	1.5
Passing #200	Limestone	2.721	-	0.2

* - average of three determinations

Table 3.3 Aggregate Gradations Used for Various Baghouse Fines Contents

	Percent Passing				
Sieve No.	JMF	JMF for 0%	JMF for 3.0%	JMF for 6.0%	JMF for 9.0%
3/4"	100	100	100	100	100
1/2"	90-100	94.7	94.8	95.0	95.1
3/8"	-	84.0	84.5	85.0	85.5
No. 4	44-74	56.5	57.5	59.0	60.3
No. 8	28-58	39.3	41.2	43.0	44.8
No. 16	20-46	28.7	30.9	33.0	35.1
No. 30	13-33	18.1	20.5	23.0	25.5
No. 50	5-21	7.4	10.2	13.0	15.8
No. 100	3-16	4.3	7.1	10.0	12.9
No. 200	2-10	0	3.0	6.0	9.0

Table 3.4 Physical Properties of Asphalt Cement

Before Aging	AC-5	AC-10	AC-20
Penetration (1/10mm) (25°C)	112	60	46
Soft Point (°C)	44	49	50
Ductility (cm) (25°C)	> 150	> 150	> 150
Viscosity (poise) (60°C)	551	1275	2378
Viscosity (cSt) (135°C)	198	312	356
After Aging 2.5 hrs			
Penetration (1/10mm) (25°C)	99	50	38
Soft Point (°C)	45.5	50.0	53.5
Ductility (cm) (25°C)	> 150	> 150	> 150
Viscosity (poise) (60°C)	689	2233	3714
Viscosity (cSt) (135°C)	235	392	495
After Aging 5.0 hrs			
Penetration (1/10mm) (25°C)	85	40	27
Soft Point (°C)	49.5	52.5	56.0
Ductility (cm) (25°C)	> 150	> 150	> 150
Viscosity (poise) (60°C)	1404	3656	5700
Viscosity (cSt) (135°C)	490	875	2707

3.2 Equipment

The major pieces of equipment used in this study include the gyratory testing machine, the resilient modulus test equipment, the indirect tensile test machine, the Hveem stabilometer and Riehle compression machine, the Marshall testing equipment, the indirect creep test equipment, the forced draft oven (aging), low temperature chamber and the asphalt cement physical properties test equipments. They are described in the following sections. The test procedures are not included herein, but they are presented in later chapters relevant to their usages. Figure 3.3 show the gyratory testing machine used in this study.

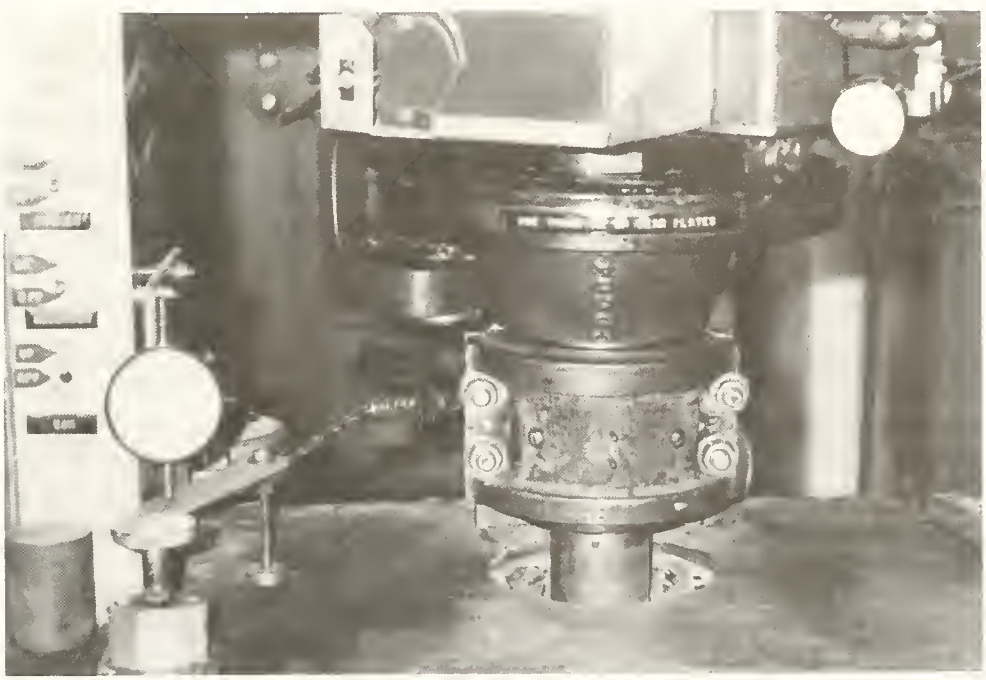


Figure 3.3 Gyratory Testing Machine

CHAPTER 4

LABORATORY TEST PROCEDURES

4.1 Introduction

This chapter presents the laboratory test procedures and testing sequence in this study. It includes the descriptions of (1) flow chart and testing sequence, (2) preparation, batching, and mixing, (3) compaction, (4) resilient modulus test, (5) indirect tensile test, (6) Hveem stability test, (7) environmental aging test, (8) water sensitivity test, (9) creep test, (10) asphalt physical properties test.

4.2 Testing Sequence and Flow Chart

The testing sequence on the specimens was designed so that as much information and parameters as possible could be collected from every laboratory testing sample. The general testing sequence and flow chart for the asphalt mastic in this study is presented in Figure 4.1. Figure 4.2 shows the general testing sequence and flow chart for asphalt paving mixtures containing different baghouse fines and asphalt cement content. The resilient modulus is a non-destructive test, so the same specimens were used repeatedly at various temperatures and conditioning. After the resilient modulus test had been performed on each specimen, some of specimens were evaluated in the Hveem stabilometer or in the creep test and then in the indirect tensile test.

The testing sequences for the asphalt paving mixture where the

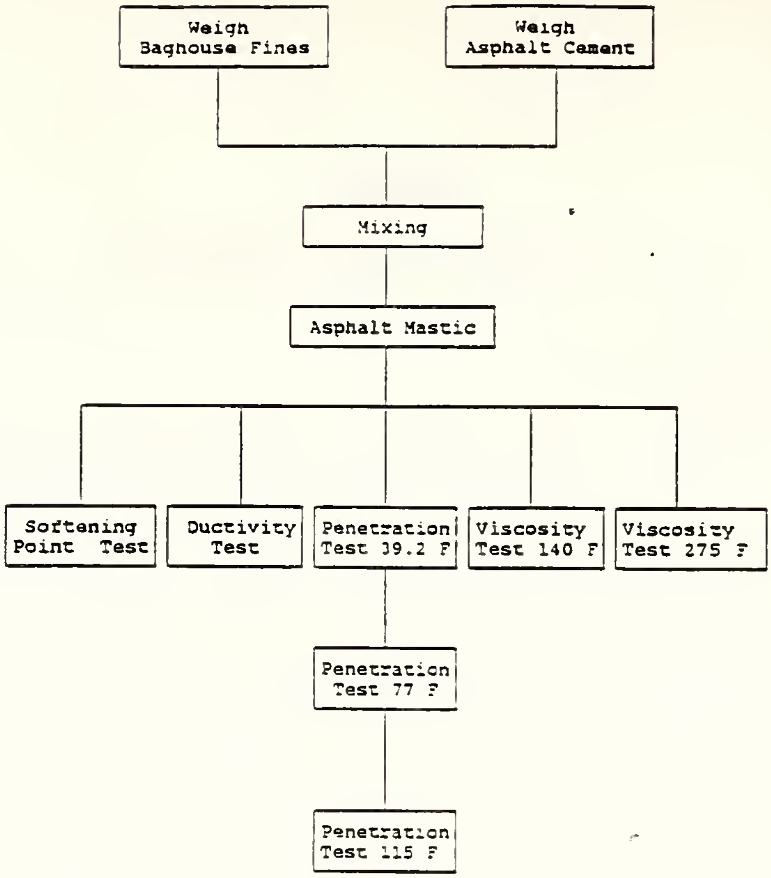


Figure 4.1 Flow Chart of Asphalt Mastics Test Procedure

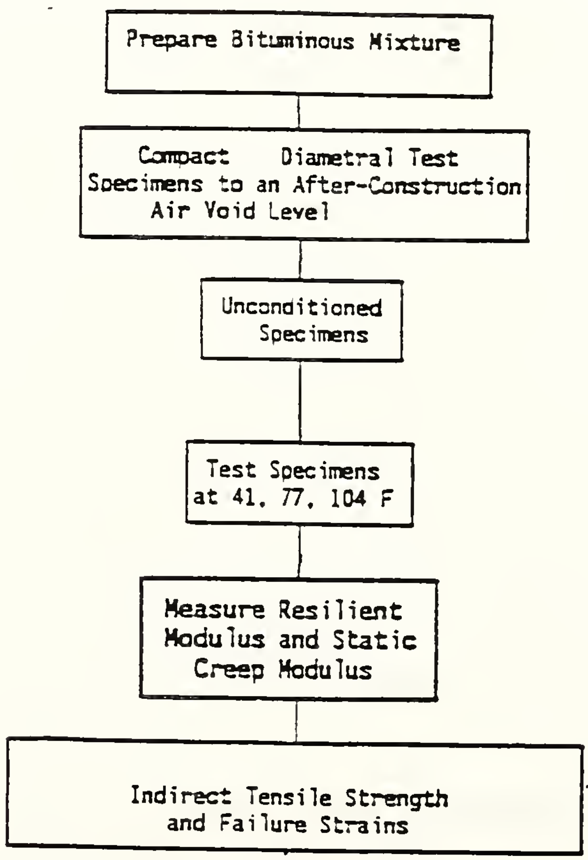


Figure 4.2 Flow Chart of Asphalt Paving Mixtures Test Procedure Under No Conditioning

volume of baghouse fines plus asphalt cement were held constant are given in Figure 4.3 and 4.4. Specimens environmental conditioning evaluated in the resilient modulus, Hveem stability test, and indirect tensile test.

4.3 Preparation, Batching and Mixing

Batch weights of the test specimens of the desired aggregate gradation were determined from either prior experience or the compaction of trial samples. In this study, aggregates separated into component sieve-size fractions were batched according to the job-mix formula (Table 3.4). Batches of 1100 grams each were used throughout the research and the batching was weighted with cold dried aggregates using a Ohaus electric scale sensitive to 0.1 gram.

Prior to mixing with asphalt, the aggregate batches were heated to 325 ± 5°F in a constant temperature controlled oven. The asphalt was heated separately to 300 ± 5°F in another small oven. Mixing bowl, paddle, and other utensils were also heated to approximately 325°F to prevent excessive heat loss during mixing. The hot aggregate was placed in the heated mixing bowl, and then the mixing bowl was placed on the scale and the specified percentage of heated asphalt (by weight of dry aggregate) was added. The mixing was accomplished with a Hobart (Model A-200) electric mixer modified with a special mixing paddle and a scraper. Mixing was completed by intermediate speed in one minute. If the mixtures tended to turn with the paddles during the mixing

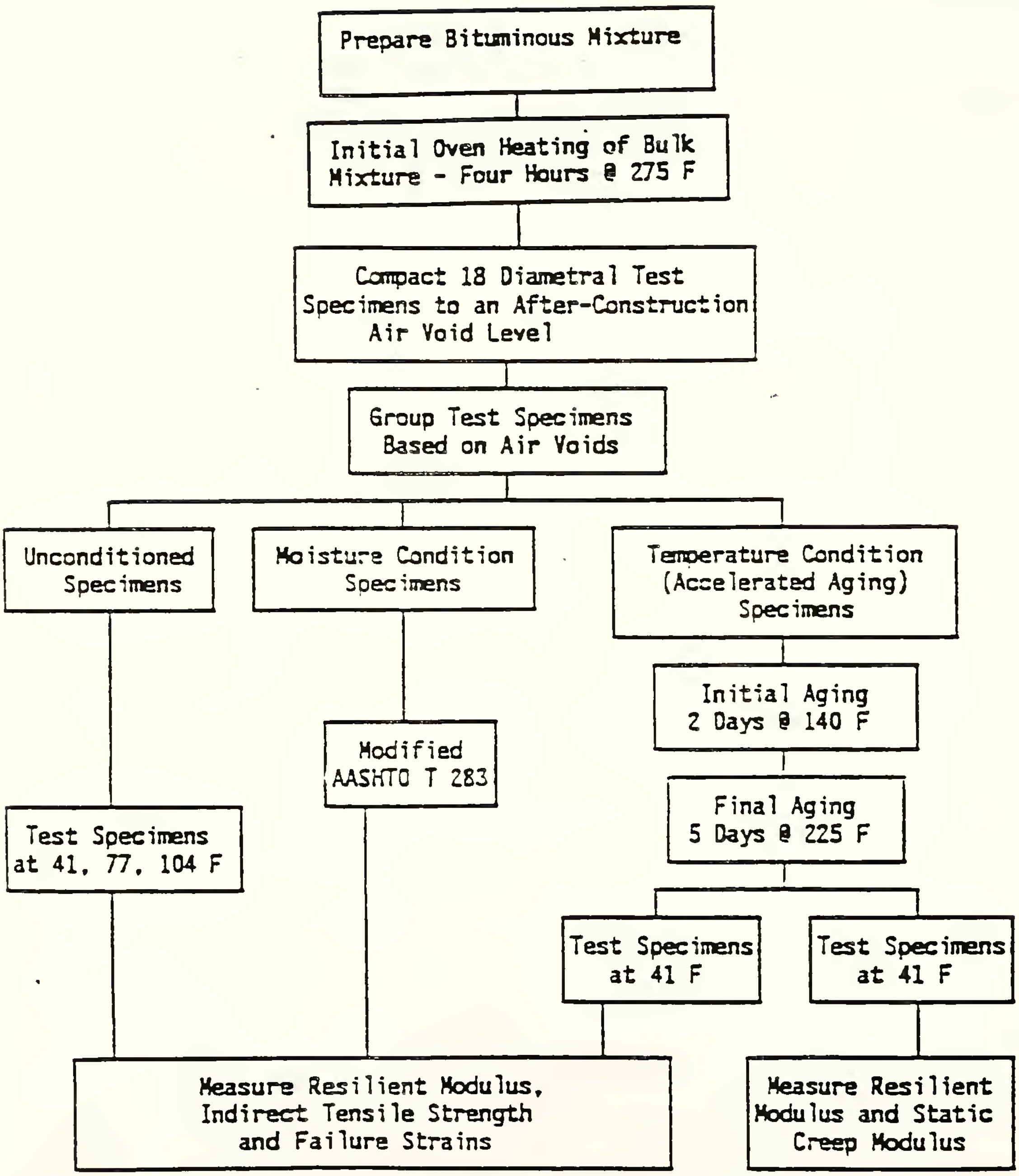


Figure 4.3 Flow Chart of Asphalt Paving Mixtures Test Under Aging and Water Saturation Conditioning

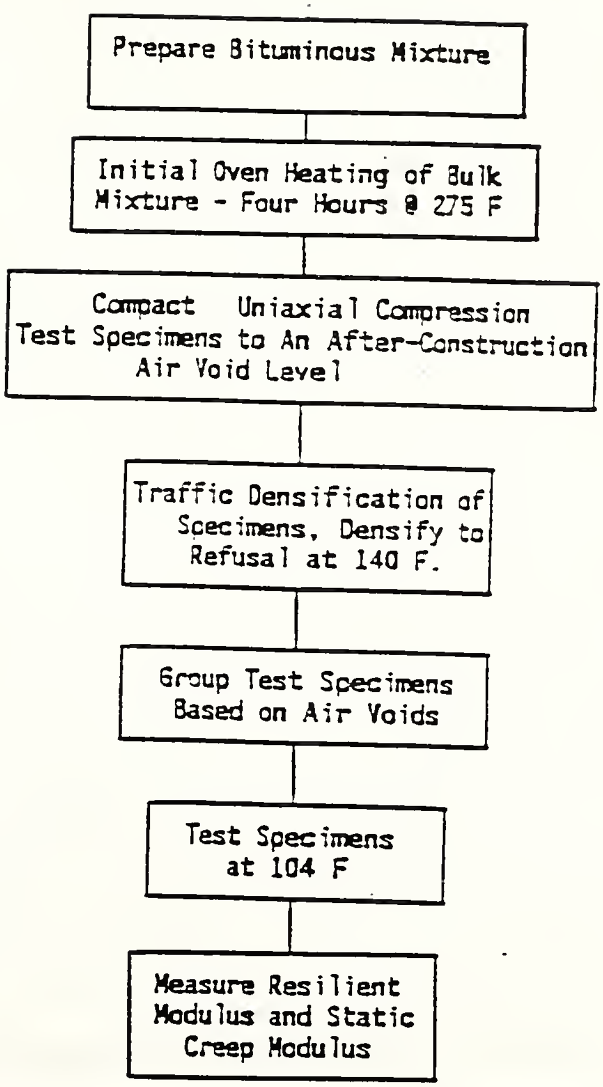


Figure 4.4 Flow Chart of Asphalt Paving Mixtures Test Procedure Under Densification Conditioning

operation, a spatula was inserted into the mixing bowl to increase agitation. Care should be exercised to assume coating of all aggregate particles. The mixing bowl and paddles were removed and the adhered mixture was scraped off and the mixture was loosened from the sides of the bowl with a large spatula.

The loose mixtures were subjected to two types of treatments used in this study: no curing and aging to simulate asphalt plant production, no curing of the mixture involved mixing followed by compaction. Asphalt plant hardening was simulated by aging the loose mixture in a force draft oven at 275°F for a period of 4 hours followed by compaction. The loose mixtures were transferred to an 11" x 7" x 1 1/2" pan and placed in a Hotpack (Model 1412) oven with forced draft air circulation. The open air temperature was maintained at 275° ± 5°F.

4.4 Compaction

The gyratory compaction was accomplished using the gyratory testing machine (Model 4C) as shown in Figure 3.4. The base plate, mold were preheated at 240°F to 260°F. The gyratory chunk heater should be turned on 1/2 hour prior to compaction and set for a 140°F temperature. The heated mold, base plate, and paper disc were placed on the carving tray. Using a wide mouth funnel, empty the contents of the pan into the mold. The flat side of a spatula may be used to push the mixture into the mold to permit the funnel to be removed. A paper disc was placed on the mixture and with a 4-inch diameter plunger compress the mixture was compressed by hand until it was 3/8 to 1/2 inch below the top of the mold.

The mold was clamped in the GTM which has been previously set for a 1 degree angle of gyration and different ram pressure. Initial compaction was carried out in all cases with the oil-filled upper roller and a specimen temperature of about 250 ± 5°F. Ram pressures used were 100 or 200 psi. The conditions of the test were chosen depending on simulating compaction in the field by construction equipment and by traffic situation. The numbers of revolutions used in the compaction were 30, 60, 120, and 180, also depending on field or traffic condition. GTM was used to study traffic densification at selected asphalt cement and baghouse fine contents. The compacted specimens were allowed to cool prior to being placed in a 140°F oven. The GTM was set at a 1 degree angle, 200 psi ram pressure, and 20 psi oil-roller pressure. The mold chuck heater was set at 140°F and traffic densification simulation test were performed up to a maximum of 300 revolutions. Initial sample height readings were obtained prior to densification.

After completion of compaction in Marshall or the gyratory testing machine, specimens were tested in indirect tensile strength test, resilient modulus test, Hveem stability test, and unit weight test. Figure 4.5 shows the specimen extruded from mold being prepared for the various test.

4.5 Resilient Modulus Test

The height of the specimens were measured and then placed in a constant temperature controlled room for at least 24 hrs. A dummy specimen with a dial stainless steel thermometer inserted inside was placed in the same condition as that of the test specimens. It was used to measure the test temperature of the specimens just before the test. The tests were conducted at 39.2°F (4°C), 73°F (23°C), and 104°F (40°C). The specimen was placed in the resilient modulus test yoke assembly. The specimen was aligned with one of crossed lines horizontal and the other vertical. The specimen was centered in the yoke. The side-mounting screws were tightened gently. A 90-degree angle square or level may be used for alignment. The specimen was aligned directly under the plunger-load cell. The centers of plunger, load cell and specimen should all lie on a common axis. The transducer should lie in a diametrical plane horizontal to the vertical axis of plunger-load cell specimen alignment. The transducer adjusting screws should be adjusted to allow the transducer tip to make contact with the specimen. During the testing, a load of 0.75 second duration was applied every 3 seconds. The magnitude of this load was varied from 25 lbs to 200 lbs depending on the testing temperature. The magnitude of the load, the deformation, and the specimen temperature were all recorded. After the deformations for the 10 pulse loads were taken, the specimen was rotated by 90 degrees and tested again following the same procedure above. If the differences between deformation values were found to be larger than 10% for two positions, the specimen was tested at a third position and the unreasonable results were discarded. The resilient modulus was calculated using the equation 5.4 in next chapter. ASTM

Designation D4123 issued the standard method for indirect tensile test for resilient modulus of bituminous mixtures (26).

4.6 Indirect Tensile Test

The indirect tensile test was conducted on a Marshall test apparatus. During the testing, the specimen was loaded in a frame which has top and bottom loading strips both 0.5 inch wide. The contact areas of these strips are curved to conform the circumference of the specimen. A standard Marshall specimen was used in this study. The tests were conducted at 39.2°F (4°C), 73°F (23°C) and 104°F (40°C) depending on the conditioning of asphalt paving mixtures. The height of the test specimen was measured and then the specimen was left in a temperature controlled chamber for at least 12 hrs so as to stabilize the specimen. A dummy specimen with a dial stainless steel thermometer inserted inside was placed in the same environment as that of the specimen just before the test. Place the test specimen in the loading apparatus, positioned as stated in Test Method ASTM D4123 (26), and adjusted.

The electronic measuring system was balanced as necessary. The load was then applied at a rate of 2 inches per minute until failure and monitored with an electronic load cell. Vertical deformations were recorded by the strip graph recorder. Both load and deformation were plotted on the chart recorder. During the load application, changes in the output voltages of the load cell were converted to movements of the recording pens. The sensitivities of the recorder and the position of the pen were so adjusted to obtain recording within the chart. The load at failure, determined from the strip graph, was used to calculate the indirect tensile strength.

4.7 Hveem Stabilometer Test

The Hveem stabilometer is the standard device that is used for the Hveem stability (S-value) test. The standard procedures for the stabilometer test is given in ASTM D1560 (27) or Asphalt Institute MS-2 (22) were used in this study. In this test, the horizontal pressure for a vertical load of 5000 lb was determined. The displacement on specimen was also determined.

The horizontal pressure, deformation of specimen and vertical load were used to calculate the stability of asphalt paving mixtures. When the specimen height is not between 2.40 and 2.59 inches, a conversion chart was used applied to correct the Hveem stability values to a effective specimen height of 2.5 inch.

4.8 Water Sensitivity Test

The test used in this study for evaluating resistance to moisture damage was performed in accordance with AASHTO T-283 (28) or ASTM D4867 (29). They were a modification of the Lottman test that was originally used by Tunnicliff. The procedure for moisture sensitivity test is as follows:

(1) The specimen was saturated by submerging it in water and applying a partial vacuum of 20-in. (508 mm) Hg for a short time such as five minutes. The vacuum was removed and the

specimen submerged in water for 30 minutes.

(2) The bulk specific gravity by AASHTO T-186 or ASTM D2726. The volume of absorbed water and degree of saturation was determined.

(3) The vacuum saturated specimen was covered tightly with a plastic film and placed in a plastic bag which in turn was placed in freezer at 0.5 ± 3.6°F (-18 ± 2.0°C) for at least 16 hours.

(4) After 16 hours, the specimens were placed into 140 ± 1.8°F water bath for 24 hours. After 3 minutes of immersion and the surface of the specimen had thawed the bag and wrapping from the specimens were removed.

(5) After 24 hours in the 140°F (60°) water bath, the specimen was removed and placed in a water bath already at 73°F for 2 hours. The specimen was tested in the resilient modulus device and indirect tensile test apparatus.

4.9 Environmental Aging Test

The specimens were placed in a forced draft oven at a temperature of 140°F (60°C) for approximately 48 hours plus or minus 30 minutes. After initial aging, the temperature of the forced draft oven was elevated to 225°F for an additional 5 days of aging. After aging, the specimens were removed from the oven and placed in the temperature controlled chamber and stored for at least 12 hours prior to determining the resilient modulus and indirect tensile strength.

4.10 Creep Test

The indirect creep test makes use of the same kind of apparatus as the resilient modulus device. The test specimen is placed in the loading apparatus, positioned as stated in Test Method ASTM D4123. The electronic measuring system is adjusted and balanced following the instructions and operation manual (30). The specimen is preconditioned by applying a repeated haversine to the specimen without impact using a loading frequency of 1 cycle per second for 1 minute. At the end of preconditioning step, the horizontal recoverable deformation is measured to calculate the resilient modulus in accordance with ASTM D4123. The recommendation load range to be used for indirect tensile or creep compliance testing is that to induce 5 to 10 percent of the indirect tensile strength. After the samples had been preconditioned, a static load was applied to the specimen for a period of 10 minutes plus or minus 15 seconds. After the fixed load had been applied for over 10 minutes, it should be released and the rebound or resilient deformation recorded for another 10 minutes of no load. After 10 minutes, the amount of permanent deformations should be measured and recorded from the strip chart recorder.

4.11 Asphalt Cement and Baghouse Fine Test Method

1. Asphalt Physical Properties
   (1) Penetration ASTM D5
   (2) Soft Point ASTM D2398

(3) Ductility ASTM D113

(4) Viscosity ASTM D2170 & D2171

(5) Thin Film Oven Test ASTM D1754

2. Filler and Fines

(1) Hydrometer Method ASTM D422

(2) Kerosene Method

(3) Dry Compaction Method Modified ASTM D698

(4) PH Value

Figure 4.5 Curing of Asphalt Paving Mixtures Specimens

CHAPTER 5

DESIGN OF THE EXPERIMENT

5.1 Introduction

The main objective of this portion of the study is to evaluate the feasibility of using the gyratory testing machine to prepare and design asphalt paving mixtures for long term performance which contain baghouse fines. The long-term behavior of baghouse fines asphalt mixtures are dependent upon the mineralogical characteristics of baghouse fines, additional traffic compaction, aging, temperature, and water sensitivity. The behavior of a wide variety of baghouse fines asphalt mixtures have to be fully understood in order to evaluate the feasibility of predicting long time performance from short-term results, the effects of these five factors.

Seven sets of experiments are presented that will focus on the behavior of a wide variety of asphalt mastics and asphalt paving mixtures containing baghouse fines and mineral fillers. Specimens would be compacted with the gyratory machine and gyratory indices will be obtained during the compaction process. These gyratory indices are to be correlated to the long-term behavior of these mixtures as measured by the resilient modulus, Hveem stability, indirect tensile strength, creep, aging, and water sensitivity test.

This chapter presents the description of the response variables and independent variables used, and the experimental design for investigation.

5.2 Response Variables

The response variables used in the laboratory study include the gyratory indices generated by the gyratory testing machine during the compaction process and other variables measured at some specific times after compaction and conditioning.

5.2.1 Gyratory Indices

The gyratory motion experienced by specimen, as specimen is being compacted by the gyratory testing machine, is recorded by a gyrograph and the magnitude of gyratory angle is indicated by the width of the gyrograph. Gyratory indices can then be obtained from the gyrograph.

(1) Gyratory Elasto-Plastic Index (GEPI)

$$GEPI = \frac{\text{Minimum Intermediate Gyrograph Width}}{\text{Initial Gyratory Angle}} \qquad 5.1$$

(2) Gyratory Stability Index (GSI)

$$GSI = \frac{\text{Maximum Gyrograph Width}}{\text{Minimum Intermediate Gyrograph Width}} \qquad 5.2$$

(3) Gyratory Compactibility Index (GCI)

$$GCI = \frac{\text{Unit Weight at 30 Revolutions}}{\text{Unit Weight at 60 Revolutions}} \qquad 5.3$$

The gyrograph band width is obtained by counting vertically the total number of small divisions over which the gyrograph extends (Figure 3.5).

5.2.2 Resilient Modulus (M_R)

The resilient modulus is defined as the ratio of the applied stress to the resilient strain (recoverable strain) when a dynamic load is applied.

$$M_R = \frac{P\ (\nu + 0.2734)}{td} \qquad 5.4$$

where P = the vertical load, pounds

d = horizontal deformation, inches

ν = poissons ratio

t = thickness of specimen, inches

5.2.3 Stabilometer Resistance Value (S-Value)

The S-value is an empirical number which indicates the stability or resistance of pavement materials to plastic deformation and is generally used in the evaluation of asphalt paving mixtures. Marshall size specimens are subjected in the stabilometer to a vertical pressure of 400 psi at 60°C temperature. The S-value is then calculated from the horizontal pressure and the displacement of the specimen according to an empirical formula.

$$S = \frac{22.2}{\frac{P_h D_2}{P_v - P_h} + 0.222} \qquad 5.5$$

where S = stabilometer value

D_2 = displacement of specimen

P_v = vertical pressure (typically 400 psi)

P_h = horizontal pressure

= stabilometer pressure gauge reading taken at the instant P_v is 400 psi

5.2.4 Indirect Tensile Value

The static indirect tensile test was included in this study. The variables obtained from this test and used in the analysis are Indirect Tensile Strength (ITS), Indirect Tensile Stiffness (ITST), Indirect Tensile Index (ITI), and Failure Tensile Strain (35).

(1) Indirect Tensile Strength (ITS)

The Indirect Tensile Strength is defined as the maximum load required to produce failure of a standard Marshall specimen in Indirect Tensile Test. It is an indication of the ability of an asphalt paving mixture to resist the tensile stress.

(2) Indirect Tensile Stiffness (ITST)

The Indirect Tensile Stiffness is defined as the slope of the linear portion of the load-deformation plot obtained in indirect tensile test. It is generally used in conjunction with the indirect tensile strength to evaluate the performance of asphalt paving mixtures.

(3) Indirect Tensile Index (ITI)

The indirect tensile index is defined as the area of the load-deformation plot obtained from the indirect tensile test. Since the units of the index (ITI) are in terms equivalent to energy, the ITI may be used as an indication of the toughness of asphalt paving mixtures.

(4) Failure Tensile Strain

The failure tensile strain is defined as the total horizontal tensile strain at failure. It is another parameter of the indirect tensile test that may be used to provide a better standard for judging the performance of asphalt paving mixtures.

5.2.5 Creep Compliance and Mix Stiffness

The strain in the creep test obtained under constant load is observed as a function of time.

(1) Creep Compliance

The function of strain, $\epsilon(t)$, when divided by the constant stress σ_o, is called the creep compliance denoted by J(t) (32,36,37) or

$$J(t) = \epsilon(t)/\sigma_o \qquad 5.6$$

The Burgers model is a general form of the creep compliance. The creep compliance J(t) is calculated as

$$J(t) = 1/E_1 + (1/E_2)\ [1 - \exp\ (-t/\tau_2)] + t/\eta_3 \qquad 5.7$$

where E_1 = the modulus of elasticity of Maxwell unit

E_2 = the modulus of elasticity of Voigt unit

η_3 = the viscosity of the Maxwell unit

η_2 = the viscosity of the Voigt unit

τ_2 = the retardation time = η_2/E_2

All the parameters can be obtained by nonlinear regression analysis method.

(2) Mix Stiffness

Analysis of the data from the creep test can produce an indicator of mixtures stiffness. This indicator is identified as a modulus S_{mix} (31) that defines the relationship between a constant load and deformation as a function of time and temperature.

$$S_{mix}(T,t) = \sigma_o/\epsilon(T,t) \tag{5.8}$$

where σ_o = axial loading stress

$\epsilon(T,t)$ = total horizontal strain, at given time and temperature

5.2.6 Temperature Susceptibility of Asphalt Mastics

Four measures of temperature susceptibility were used in this study.

(1) Penetration Index (PI)

$$PI = Penetration\ Index = \frac{20 - 500\ FX}{50\ FX + 1} \tag{5.9}$$

where $FX = \dfrac{\log(800) - \log(Pen77\,°F)}{SP - 77\,°F}$

SP = softening point of asphalt cement (°F)

(2) Penetration Ratio (PR)

$$PR = \text{Penetration Ratio} \qquad 5.10$$

$$= \frac{\text{Penetration at } 39.2^0\text{F}}{\text{Penetration at } 77^0\text{F}} \times 100\%$$

(3) Pen-Vis Number (PVN)

PVN1 = Pen-Vis Number (77°F - 275°F)

$$= \left[\frac{-1.5\ (L - \log \eta_{275\,°F})}{(L-M)}\right] \qquad 5.11$$

where L = 4.050 - 0.79674 log (Pen 77°F)

M = 3.46289 - 0.61094 log (Pen 77°F)

η = viscosity of asphalt cement at 275°F (135°C)

Pen = Penetration at 77°F (25°C)

PVN2 = Pen-Vis Number (77°F - 140°F)

$$= \left[\frac{6.489 - 1.590 \log P - \log \nu}{1.050 - 0.2234 \log P}\right] (-1.5) \qquad 5.12$$

where P = penetration at 77°F (25°C)

ν = viscosity at 140°F (60°C)

(4) Viscosity Temperature Susceptibility (VTS)

$$VTS = Viscosity\ Temperature\ Susceptibility \tag{5.13}$$

$$= \frac{\log \eta_{140\,°F} - \log \eta_{275\,°F}}{\log 140\,°F - \log 275\,°F}$$

where $\eta_{140\ F}$ = Viscosity at 140°F (60°C)

$\eta_{275\ F}$ = Viscosity at 275°F (135°C)

5.2.7 Water Susceptibility of Asphalt Paving Mixtures

The evaluation of moisture damage can be made by calculating the tensile strength ratio (TSR) or the resilient modulus ratio (MMR) (32) as follows:

$$TSR = \frac{ITS\ of\ conditioned\ specimens}{ITS\ of\ control\ specimens} \tag{5.14}$$

$$MMR = \frac{M_R\ of\ conditioned\ specimens}{M_R\ of\ control\ specimens} \tag{5.15}$$

5.3 Independent Variables

5.3.1 Type of Baghouse Fines

Fifteen different baghouse fines which are found in Indiana were used to mix with the asphalt cement and asphalt aggregate mixture for this study.

5.3.2 Percent of Baghouse Fines

The three levels of baghouse fines added were: 3%, 6% and 9%

by weight of the aggregate.

5.3.3 Type of Binder

The binders added to the aggregate were an AC-5, AC-10 and AC-20.

5.3.4 Percent of Binder

The three or four levels of percent binder added were 4.0%, 4.5%, 5.0% and 5.0% by weight of the aggregate. The values used were dependent upon the optimum asphalt content of the asphalt mixture.

5.3.5 Compactive Effect

The gyratory testing machine used in this study is capable of producing different compactive efforts by varying the numbers of revolutions and vertical ram pressures. The three main compactive effects used were 60, 120 and 180 revolutions at 200 psi ram pressure. The densification test required 300 revolutions to compact the asphalt paving mixtures at 60°C temperature.

5.3.6 Aging Time

Aging time is the time between the compaction and the testing of specimen. The three aging times used were 4 hours, 48 hours and 168 hours at different temperatures in a forced draft oven.

5.3.7 Water Saturation

The three conditions of water saturation used in this study were dry, vacuum, and saturation at different stages to simulate the water sensitivity in field.

5.3.8 Testing Temperature

The three levels of test temperature used in this study were 4°C, 23°C and 40°C (39.2°F, 73°F and 104°F).

5.4 Experimental Designs

5.4.1 Design No. 1

The first set of experiments dealt with different types and amounts of baghouse fines combined with asphalt cement. The experimental design is shown in Table 5.1. The factors studied were different types of baghouse fines (15 levels), percent of baghouse fines (3 levels), one type of asphalt cement (1 level), and the testing temperature (5 levels) as independent variables. The dependent variables are Penetration Index, Penetration Ratio, Penetration Viscosity Number, Viscosity Temperature Sensitivity, softening point temperature, ductility, viscosity, and penetration.

5.4.2 Design No. 2

The experimental design for the second set of experiments dealt with different types and amounts of baghouse fines mixed with aggregate containing different percents of asphalt cement by

Table 5.1 Experimental Design No. 1

Asphalt Mastics Characteristics
(Baghouse Fines)

	Temp	Baghouse Fines**** 1			2			3		
		Baghouse Fines Content* (%)								
	(°F)	3%	6%	9%	3%	6%	9%	3%	6%	9%
	40	xx***	xx	xx	xx	xx	xx	xx	xx	xx
Pene.**	77	xx	xx	xx	xx	xx	xx	xx	xx	xx
	115	xx	xx	xx	xx	xx	xx	xx	xx	xx
Visc.**	135	xx	xx	xx	xx	xx	xx	xx	xx	xx
	275	xx	xx	xx	xx	xx	xx	xx	xx	xx
SF.**		xx	xx	xx	xx	xx	xx	xx	xx	xx
Duct.**	77	xx	xx	xx	xx	xx	xx	xx	xx	xx

* : Percent of baghouse fines content = 0 is not shown on the table.

** : Pene. = Penetration, Visc. = Viscosity, SF = Softening Point, Duct. = Ductility.

*** : Test data; dependent variables: (1) penetration index, (2) penetration ratio, (3) penetration viscosity number, (4) viscosity temperature sensitivity.

****: Independent variable: type of baghouse fines (different surface area, particle size, mineralogical composition, unit weight, PH value) weight.

The experimental design No. 2 is shown in Table 5.2. A compactive effort of 200 psi vertical pressure was used. The main factors studied were the different types of baghouse fines (3 levels), the percent baghouse fines added, the percent asphalt cement added (each 3 level) and revolutions in gyratory testing machines (4 levels). The compaction temperature was 250°F.

5.4.3 Design No. 3

Design No. 3 involved the oven simulated aging is executed at different times in order to study the asphalt mixture performance. The experimental design is presented in Table 5.3. Three aged conditions (4 hrs, 48 hrs, 168 hrs) of the asphalt mixture are used. The other factors studied are the baghouse fines (4 levels), the testing temperature (3 levels) and the percent of asphalt cement added to hold the volume of baghouse fines plus the binder content constant.

5.4.4 Design No. 4

Design No. 4 evaluated the effects of water on asphalt paving mixtures containing baghouse fines. Three different moisture conditions in asphalt paving mixtures were used. The experimental design is shown in Table 5.4. Three moisture conditions (dry, partial vacuum, saturated), 3 levels of constant volumes of baghouse fines and asphalt cement content, the baghouse fines (3 levels), and the testing temperatures (3 levels) were independent

Table 5.2 Experimental Design No. 2

Asphalt Paving Mixtures Containing Baghouse Fines

		Baghouse Fines								
		1			2			3		
		Baghouse Fines Content (%)								
AC Content (%)	Revolutions	3%	6%	9%	3%	6%	9%	3%	6%	9%
4.0%	30	xx*	xx	xx	xx	xx	xx	x	xx	xx
	60	xx	xx	xx	xx	xx	xx	x	xx	xx
	120	xx	xx	xx	xx	xx	xx	x	xx	xx
	180	xx	xx	xx	xx	xx	xx	x	xx	xx
4.5%	30	xx	xx	xx	xx	xx	xx	x	xx	xx
	60	xx	xx	xx	xx	xx	xx	x	xx	xx
	120	xx	xx	xx	xx	xx	xx	x	xx	xx
	180	xx	xx	xx	xx	xx	xx	x	xx	xx
5.0%	30	xx	xx	xx	xx	xx	xx	xx	xx	xx
	60	xx	xx	xx	xx	xx	xx	xx	xx	xx
	120	xx	xx	xx	xx	xx	xx	xx	xx	xx
	180	xx	xx	xx	xx	xx	xx	xx	xx	xx

*: Test data; dependent variables: GEPI, GSI, GCI, M_R, S, ITS, ITST, ITI, and rd.

2 samples per cell for GEPI, GSI, GCI, M_R, S, ITS and rd test.

1 sample per cell for creep test.

Table 5.3 Experimental Design No. 3

Asphalt Paving Mixtures Containing Constant Volume of Baghouse Fines and Asphalt Cement (Aging)

		Baghouse Fines 1				Baghouse Fines 2				Baghouse Fines 3			
	B/A Weight Ratio	88/44	65/49	50/54	35/59	88/44	65/49	50/54	35/59	88/44	65/49	50/54	35/59
Aging	Temp (°C) \ Asphalt Cement Content (%)	3.8%	4.3%	4.8%	5.3%	3.8%	4.3%	4.8%	5.3%	3.8%	4.3%	4.8%	5.3%
0 hr	4	xx	xx*	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
4 hrs	4	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
48 hrs	4	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
168 hrs	4	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx

* : Test data; dependent variables: M_R, S, ITS, ITI, GEPI, GSI, GCI and rd. 2 samples per cell for M_R, GEPI, GSI, GCI and rd test.

**: 1 sample per cell for ITS, ITI, and S test.

Table 5.4 Experimental Design No. 4

Asphalt Paving Mixtures Containing Constant Volume of Baghouse Fines and Asphalt Cement (Water Sensitivity)

		Baghouse Fines 1			Baghouse Fines 2			Baghouse Fines 3		
		B/A Weight Ratio								
		65/49	50/54	35/59	65/49	50/54	35/59	65/49	50/54	35/59
		Asphalt Cement Content (%)								
Time	Temp (°C)	4.3%	4.8%	5.3%	4.3%	4.8%	5.3%	4.3%	4.8%	5.3%
0 hr	4	xx*	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx
0.1 hr	4	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx
16 hrs	4	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx
40 hrs	4	xx	xx	xx	xx	xx	xx	xx	xx	xx
	23	xx	xx	xx	xx	xx	xx	xx	xx	xx
	40	xx	xx	xx	xx	xx	xx	xx	xx	xx

* : Test data; dependent variables: M_R, ITS, ITI, GCI, GSI, GEPI, and rd.
2 samples per cell for M_R, GEPI, GCI, GSI, and rd test.

**: 1 sample per cell for ITS, and ITI test.

variables. The resilient modulus, indirect tensile strength, and water absorption were dependent variables.

5.4.5 Design No. 5

The experimental design No. 5 is shown in Table 5.5. All the independent variables except baghouse fines content are the same as Design No. 2. Five different kinds of fines and fillers are used. The compaction temperature of densification is 140°F (60°C). There were two levels of revolutions of gyratory testing machines to simulate the pavement under high tire pressure and heavy traffic load. The resilient modulus was determined at 3 temperature levels, and the indirect tensile test was performed at 2 levels.

5.4.6 Design No. 6

The sixth experimental design was created to study the effect of mineral fillers and baghouse fines added to the asphalt paving mixtures. Table 5.6 displays the layout of the experimental design. The factors studied are different types of mineral fillers (lime, silica flour, fly ash and silica fume) and one baghouse fines (No. 20); the percent of fillers and fines content (2 levels), the testing temperature (3 levels in resilient modulus test, 2 levels in indirect tensile test).

5.4.7 Design No. 7

Design No. 7 was established to study the effects of the different gradations of baghouse fines and mineral filler on the

Table 5.5 Experimental Design No. 5

Asphalt Paving Mixtures Containing Fine and Fillers (Densification)

		Baghouse Fines and Fillers									
		1		**2**		**3**		**4**		**5**	
	Temp (°C)	**Asphalt Content (%)**									
Revolutions		**4.5**	**5.0**	**4.5**	**5.0**	**4.5**	**5.0**	**4.5**	**5.0**	**4.5**	**5.0**
	4	**xx***	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
60	**23**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
	40	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
	4	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**
300	**23**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**
	40	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**	**xx**	**xxx**

* : Baghouse fines content equal to 6%.

**: The test parameter is the same as Design No. 4.

Table 5.6 Experimental Design No. 6

Asphalt Paving Mixture with Mineral Fillers or Baghouse Fines

	Mineral Fillers and Baghouse Fines*										
	Li		**Si**		**FA**		**SF**		**No. 20**		**No. 31**
Temp	**Baghouse Fines Content (%)***										
(°C)	**3%**	**6%**	**3%**	**6%**	**3%**	**6%**	**3%**	**6%**	**3%**	**6%**	**0%**
4	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
23	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
40	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**

* : Asphalt cement content keep 5.0% nearly to optimum asphalt content.

**: The test parameter is the same as Design No. 4.

behavior of asphalt paving mixtures. Two different gradations, coarse and fine, of the same mineralogical composition are used. The experimental design is shown in Table 5.7. Two gradations, two types of mineral fillers, two types baghouse fines, two different fillers or fines content and 3 testing temperatures were the independent variables. The resilient modulus, indirect tensile strength, and gyratory parameters were dependent variables.

Table 5.7 Experimental Design No. 7

Asphalt Paving Mixtures Containing Different Gradation of Mineral Fillers or Baghouse Fines

		Mineral Fillers and Baghouse Fines							
	Temp (°C)	Silica		Lime		No. 20		No. 6	
		Filler or Fines Content (%)							
Gradation		3%	6%	3%	6%	3%	6%	3%	6%
	4	xx	xx	xx	xxx	xx	xxx	xx	xxx
Coarse	23	xx	xx	xx	xxx	xx	xxx	xx	xxx
	40	xx	xx	xx	xxx	xx	xxx	xx	xxx
	4	xx	xx	xx	xxx	xx	xxx	xx	xxx
Fine	23	xx	xx	xx	xxx	xx	xxx	xx	xxx
	40	xx	xx	xx	xxx	xx	xxx	xx	xxx

* : The test parameters are the same as Design No. 4.

CHAPTER 6

ASPHALT MASTICS AND BAGHOUSE FINES

6.1 Baghouse Fines

Thirty different baghouse fines were sampled and collected by various INDOT personnel during the 1988 construction season. These samples had been organized as to their location in the state. These samples represent different generic types depending on the aggregate processed, such as sand, gravel, limestone and slag. Hydrated lime was used as a control mineral filler for comparison.

6.1.1 The Particle Size Distribution

These particle sizes were determined by the sedimentation process, using a hydrometer to secure the necessary data. The results for each kind of baghouse fines were calculated as cumulative particle size distributions and shown in Table 6.1 and Figure 6.1. Figure 6.1 shows a wide variation in the gradation of the different fines. These samples can be divided into three groups based on a particle size of 20 μm:

Coarse: No. 4, 6, 10, 16, 19, 21, 22, 24, 25, 29, (%≤50%)

Medium: No. 1, 3, 9, 12, 14, 20, 23, 26, 28

Fine: No. 2, 5, 7, 8, 11, 13, 15, 17, 18, 27, 30, (%>70%)

The 20 μm is considered by some investigators to be the thickness of asphalt film that coats the aggregate in asphalt paving mixtures.

6.1.2 The Surface Area

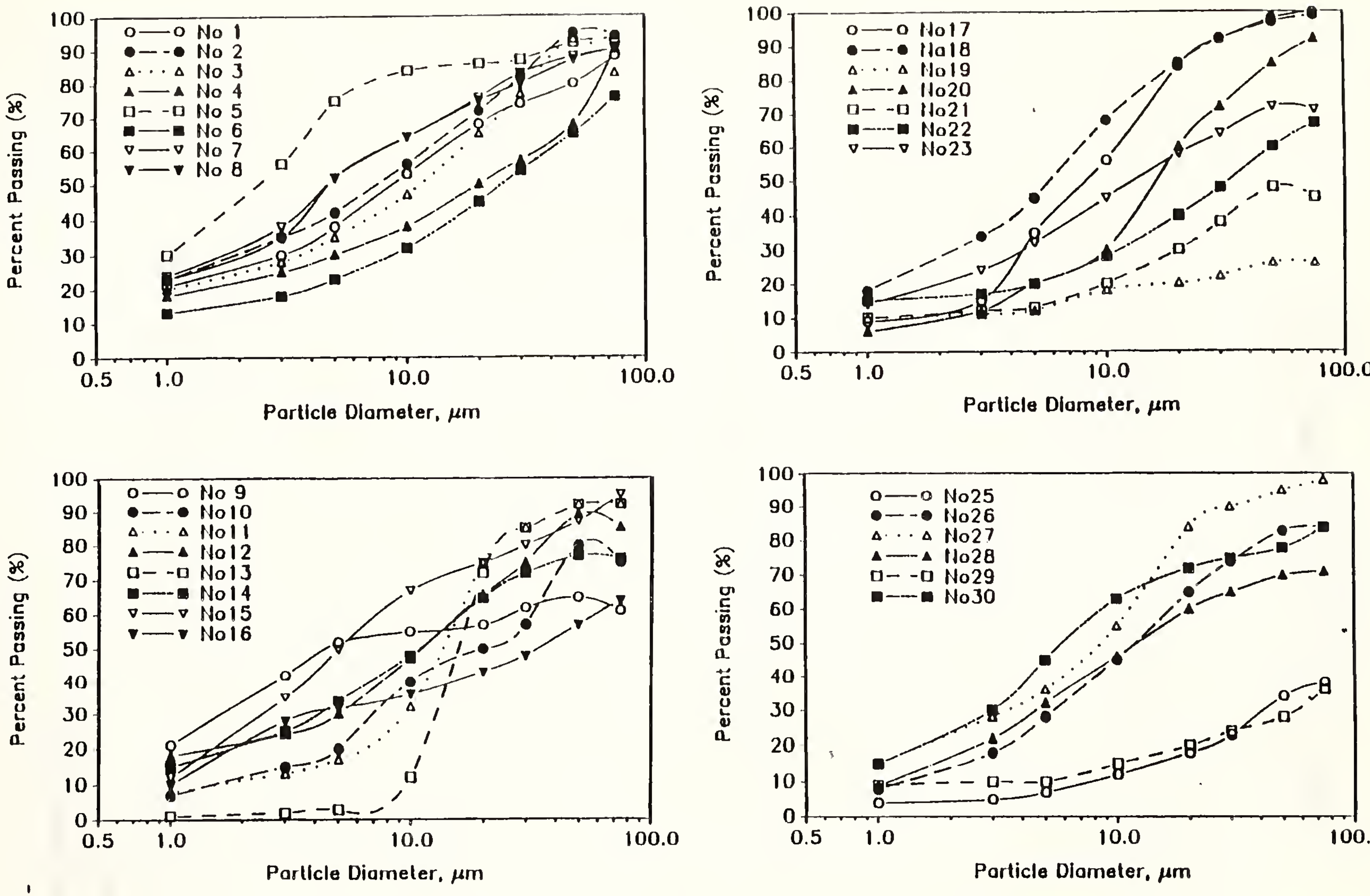


Figure 6.1 The Particle Size Distribution of Baghouse Fines

Table 6.1 Particle Size Distribution

Sample No.	Particle Size 75μ	50μ	30μm	20μm	10μm	5μm	3μm	1μm
1	88	80	74	68	53	38	30	21
2	95	94	82	72	56	42	35	23
3	83	79	77	65	47	35	28	20
4	90	68	57	50	38	30	25	18
5	93	92	87	86	84	75	56	30
6	76	65	54	45	32	23	18	13
7	90	88	83	76	64	52	38	24
8	90	87	80	75	64	52	35	23
9	67	65	62	57	55	52	42	21
10	80	75	57	50	40	20	15	7
11	92	92	85	75	32	17	13	8
12	89	85	75	66	47	30	24	18
13	95	92	85	72	12	3	2	1
14	77	76	72	65	48	34	25	15
15	95	87	80	75	67	50	35	12
16	64	57	48	43	36	32	28	10
17	100	98	92	84	56	35	15	9
18	99	97	92	85	68	45	34	18
19	26	26	22	20	18	12	11	10
20	92	85	72	60	30	20	12	6
21	48	45	38	30	20	13	12	10
22	67	60	48	40	28	20	17	15
23	72	71	64	58	45	32	24	14
24	47	43	36	28	22	15	10	8
25	38	34	23	18	12	7	5	4
26	84	83	74	65	45	28	18	8
27	98	95	90	84	55	36	28	15
28	71	70	65	60	46	32	22	9
29	36	28	24	20	15	10	10	9
30	81	78	75	72	63	45	30	15

The surface area of baghouse fines was determined by the Blaine air permeability method ASTM C204. The results for each sample were shown in Table 6.2. These samples can also be divided in three groups by surface area:

Large: No. 2, 5, 7, 8, 9, 11, 13, 18, (S.A. ≥ 8000cm^2/g)

Medium: No. 1, 3, 4, 10, 12, 14, 15, 16, 17, 20, 26, 27, 28, 30

Small: No. 6, 19, 21, 22, 23, 24, 25, 29, (S.A. < 5000 cm^3/g)

Generally, the finer the gradation of the baghouse fines, the greater the surface area.

6.1.3 The Specific Gravity

The specific gravity of the baghouse fines were determined by the classical pycmometer method ASTM D854. The results are presented in Table 6.2. Of the thirty samples tested, Samples No. 1, 3, 17, and 20 have a higher specific gravity and Samples No. 5, 15, 25, and 27 have a lower specific gravity. However, the specific gravities of all the samples are between 2.645 and 2.861.

It is necessary to understand that although in the design of hot asphalt paving mixtures, fines and fillers are proportional on the basis of weight, the volume occupied by the fines and fillers must be taken into consideration for surface area and free asphalt calculations.

The fines used in this study had specific gravities that varied less than the specification limit 0.2 from the specific gravities of the fine and coarse aggregate so no adjustments were necessary.

Table 6.2 Physical Properties of Baghouse Fines

Sample No.	Specific Gravity	Unit Weight (g/cm^3)	Surface Area (cm^2/g)	PH Value	< 20 μm (1%)
1	2.825	1.651	5774	11.1	68
2	2.806	1.446	8642	11.2	72
3	2.842	1.595	5670	9.4	65
4	2.771	1.625	5378	10.1	50
5	2.653	1.416	12254	7.3	86
6	2.730	1.598	4488	11.1	45
7	2.712	1.410	8626	11.1	76
8	2.712	1.369	9694	10.7	75
9	2.705	1.469	8320	9.3	57
10	2.692	1.624	5172	11.1	50
11	2.742	1.317	9324	11.2	75
12	2.721	1.504	5360	11.3	66
13	2.770	1.310	8276	11.3	72
14	2.730	1.464	7986	11.2	65
15	2.676	1.471	7416	10.9	75
16	2.783	1.556	5858	9.8	43
17	2.819	1.367	5784	10.1	84
18	2.739	1.326	9230	11.8	85
19	2.713	1.538	1304	11.4	20
20	2.861	1.555	5098	10.0	60
21	2.718	1.824	1952	9.3	30
22	2.798	1.724	2964	10.6	40
23	2.693	1.704	4152	9.6	58
24	2.790	1.904	2905	10.0	25
25	2.645	1.765	1158	9.6	18
26	2.703	1.495	7430	11.8	65
27	2.668	1.425	5928	8.9	84
28	2.690	1.529	5952	11.7	60
29	2.700	1.921	1464	10.3	20
30	2.703	1.538	6478	9.5	72

6.1.4 The Mineralogical Composition

X-ray diffraction analyses were carried out using Siemens D500 diffractometer to get the mineral composition. A typical x-ray diffraction of sample No. 5 and No. 10 are shown in Figure 6.2. In addition to the diffraction, x-ray fluorescence analyses were also used to find the oxide composition of baghouse fines. The results are presented in Table 6.3. A larger amount of CaO results in a larger amount of alkaline. A larger amount of SiO_2 results in a reduced amount of alkaline. Examination of the data in Table 6.3 would indicate that Sample No. 8, 9, 10, 14, 16, 17, 19, 20, 22 and 29 are siliceous baghouse fines. The others are carbonate baghouse fines. The Al_2O_3, Fe_2O_3, K_2O, SO_3 and Na_2O contents are low. Sample No. 1 has the highest MgO content, and No. 5 has the least MgO content.

6.1.5 PH Value

PH value of the baghouse fines were determined by mixing 50 grams of sample with 100 ml distilled water. The results for each sample were shown in Table 6.2. The sample No. 5 had the lowest PH value, and the sample No. 18 and 28 had the highest PH values, but nearly all of the samples had PH value that were between 9.5 to 11.0.

6.1.6 The Unit Weight and Void Content

The bulk density of the compacted baghouse fines is the dry weight of the baghouse fines when the fines were compacted into the

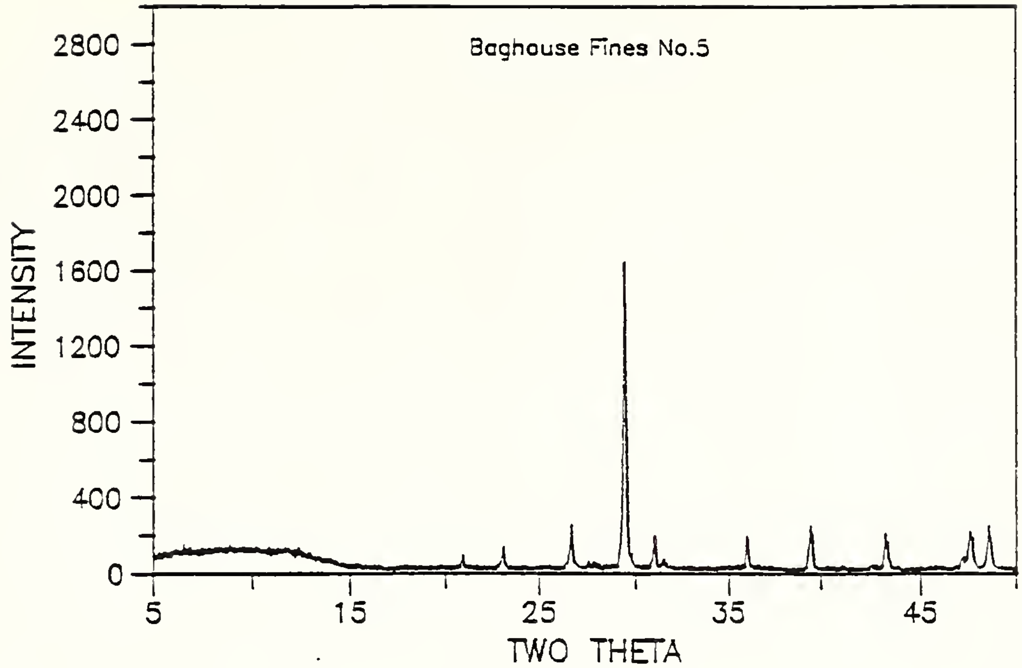


Figure 6.2 X-ray Diffraction of Baghouse Fines No. 5

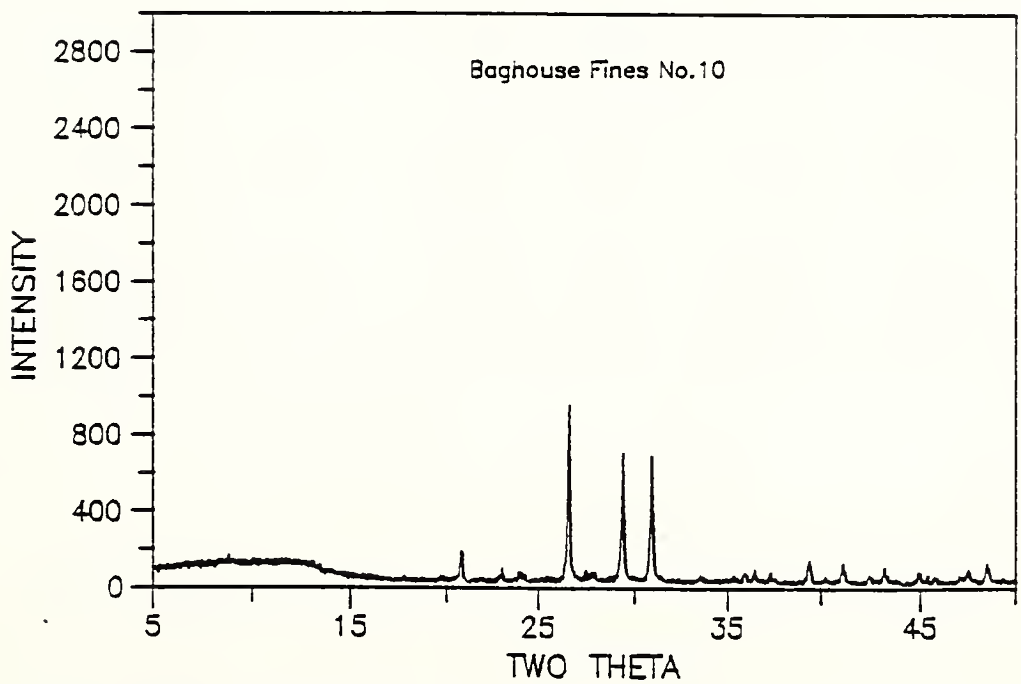


Figure 6.2 X-ray Diffraction of Baghouse Fines No. 10

Table 6.3 Oxide Analysis of Baghouse Fines

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
1	3.05	0.38	0.39	<33.17	<23.4	0.19	0.16	0.07
2	20.51	3.46	2.12	<33.17	<15.8	1.45	0.76	0.25
3	30.14	4.92	1.26	<33.17	9.19	2.75	0.55	0.30
4	16.00	2.53	1.72	<33.17	15.3	0.79	0.98	0.13
5	13.80	2.98	1.53	38.26	1.64	0.49	0.91	0.13
6	14.70	2.11	1.78	<33.17	>17.5	0.45	0.66	0.21
7	24.33	4.25	3.67	<33.17	10.95	0.32	1.07	0.36
8	31.62	4.42	4.47	29.94	13.1	0.07	1.21	0.33
9	36.96	5.33	2.97	30.94	7.15	1.48	1.00	0.43
10	41.61	4.27	3.05	29.67	7.56	0.19	0.87	0.37
11	16.20	3.43	1.77	<33.17	12.00	0.99	1.07	0.19
12	28.56	3.85	3.09	32.14	12.15	0.77	1.15	0.40
13	30.89	4.91	3.09	32.09	>13.6	1.22	1.11	0.35
14	32.19	4.91	3.33	31.94	10.03	0.37	1.28	0.40
15	15.03	2.71	3.02	<33.17	>13.6	0.93	1.02	0.19
16	42.98	6.11	2.65	30.69	7.58	1.45	0.99	0.46
17	35.43	6.71	2.94	31.89	9.13	3.20	1.37	0.41
18	28.20	4.70	4.29	30.29	>13.9	0.50	1.23	0.37
19	49.76	4.64	2.59	27.54	7.35	0.14	0.95	0.72
20	33.52	5.50	1.70	<33.17	11.40	2.30	0.85	0.29
21	22.20	2.37	1.54	<33.17	12.90	0.32	0.65	0.33
22	44.32	6.42	2.09	31.74	9.29	1.40	0.92	0.48
23	19.31	2.54	1.90	<33.17	10.40	0.32	0.77	0.27
26	16.50	2.75	1.90	<33.17	12.50	0.69	0.73	0.29
27	13.80	2.73	2.41	<33.17	11.75	0.96	0.74	0.20
28	31.40	4.11	2.80	32.09	11.70	0.48	0.99	0.49
29	45.42	3.68	1.84	32.24	4.54	0.10	0.76	0.59

small mold, divided by the total volume of the mold. The void content of the baghouse fines is defined as the bulk value of the compacted fines minus the volume of the fines solids. The results of the bulk density determinations of the baghouse fines are shown in Table 6.2. Samples No. 29, No. 24, No. 21, No. 25, No. 22 and No. 23 containing coarse particles had the higher bulk densities. Samples No. 2, No. 5, No. 7, No. 8, No. 11, No. 13, No. 17 and No. 18 containing finer particles had lower bulk densities.

The volume of asphalt required to fill these air voids is called fixed asphalt. Any asphalt that is added to a baghouse fines/asphalt mastics that is in excess of the fixed asphalt is called free asphalt, because it is free to lubricate the baghouse fines/asphalt mastics. The quantity of the free asphalt in the asphalt mastics should be used to predict the viscosity and stiffness of asphalt mastics. The percent of free asphalt is defined as the volume of the free asphalt divided by the total volume of the asphalt mastics. It is a new parameter used to describe the rheological behavior of the asphalt mastics. Table 6.4 shows the volume (%) of free asphalt of different baghouse fines. B/A is the weight ratio of baghouse fines to asphalt cement.

6.2 Asphalt Mastics

Basic physical test results of baghouse fines are contained in Table 6.1 through 6.3 and in Fig. 6.1 to Fig. 6.2. Because of constraints in time and equipment, only 17 different mastics were

Table 6.4 Volume (%) of Free Asphalt

Sample No.	B/A = 0.2	B/A = 0.4	B/A = 0.6	B/A = 0.8
1	71.85	51.63	36.97	24.63
2	67.89	44.91	28.20	14.18
3	70.84	49.88	34.60	21.76
4	71.49	51.15	36.41	24.06
5	67.53	44.65	28.21	14.54
6	71.08	50.54	35.69	23.29
7	67.27	44.05	27.30	13.32
8	66.29	42.38	25.12	10.72
9	68.59	46.34	30.26	16.89
10	71.02	51.53	37.05	24.99
11	64.89	39.91	21.84	6.74
12	70.47	49.51	34.37	21.73
13	64.64	34.41	21.12	5.81
14	68.43	46.01	29.80	16.27
15	68.69	46.58	30.67	17.92
16	66.02	41.64	29.31	9.04
17	65.13	40.33	22.40	7.42
18				
19				
20	70.05	48.49	32.78	19.51
21	74.68	56.72	43.75	32.93
22	73.08	53.83	39.84	28.11
23	72.94	53.80	40.00	28.50
24				
25	73.96	55.63	42.47	31.54
26	69.14	47.29	31.52	18.37
27	67.70	44.91	28.51	14.86
28	69.85	48.53	33.17	20.36
29	75.99	58.99	46.72	36.51
30	70.11	48.76	33.43	20.65

actually prepared and tested. Fifteen mastics involved varying blends of baghouse fines and the other two consisted of hydrated lime and silica fines.

An experimental program was established to assess the effects of different concentrations of baghouse fines on asphalt mastics. The tests of rheological properties that were conducted included the following:

(i) Penetration at 39.2°F (4°C), 77°C (25°C), 115°F (46°C)

(ii) Viscosity at 140°F (60°C), 275°F (135°C)

(iii) Ductility at 77°F (25°C)

(iv) Softening point

The results of these tests for each of seventeen baghouse fines and mineral fillers are given in Appendix A-1.

6.2.1 Penetration Test

In consideration of the fact that only a single replicate measurement at 39.2°F (4°C) and 115°F (46°C) and two replicate measurements at 77°F (25°C) were made, the following linear model was assumed:

$$Y_{ijkl} = \mu+B_i+V_j+BV_{ij}+S(BV)_{(ij)k}+d_{ijk}+T_l+BT_{il}+VT_{jl}+BVT_{ijl}+S(BV)T_{(ij)kl}+\epsilon_{ijkl} \tag{6.1}$$

where Y_{ijkl} = response variable: penetration

μ = overall mean

B_i = effect of different types of baghouse fines or mineral fillers

V_j = effect of different fines/asphalt cement ratio (volume)

T_l = effect of testing temperature

$S(BV)_{ij}$ = within error of BV combination

d_{ijk} = restriction error

ϵ_{ijkl} = experimental error

BV_{ij}, BT_{il}, $VT_{jl}...S(BV)T_{(ij)kl}$ = Effects of interactions of main factors

$i = 1, 2...17;\ j = 1, 2, 3;\ k = 1, 2, 3;\ l = 1$

ANOVA was performed on the test results using SAS/STAT computer software. Results of ANOVA are summarized in Table 6.5. A probability type I error $\alpha = 0.05$ was used which corresponds to a 95 percent level of confidence. The main effect baghouse fines, fine/asphalt cement ratio, and temperature are significant. The interaction effect such as baghouse fines * temperature, fine/asphalt * temperature etc. are also significant. Figure 6.3 illustrates the effects of the concentration of different fines on the penetration of asphalt mastics at different temperatures.

The different fines used in this study had a marked influence on the penetration versus fine concentration relationship. At all test temperatures, it appeared that high concentrations of fines reduced the penetrations of the asphalt mastics.

6.2.2 Viscosity Test

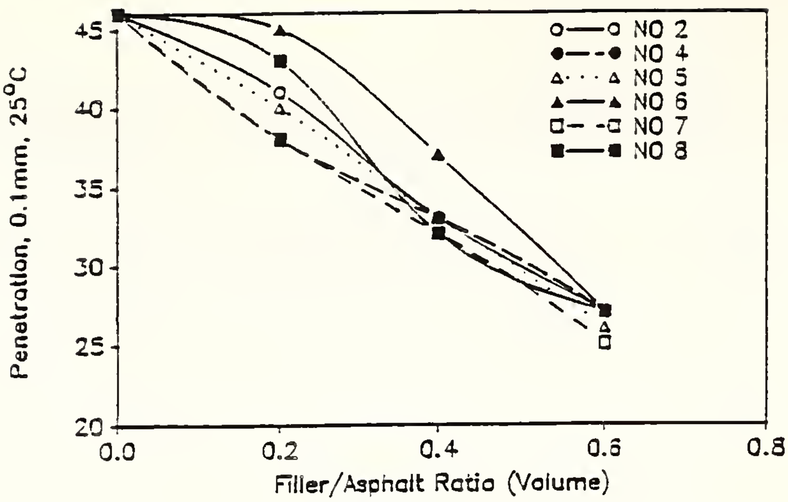
The test results as tabulated in Appendix A-2 were analyzed in a manner similar to that described in the previous Section 6.2.1.

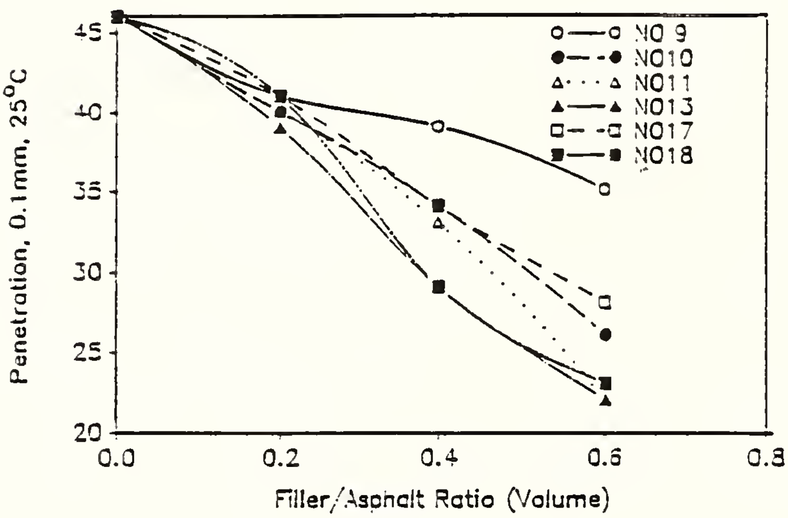
Table 6.5 ANOVA Results for Penetration (Design No. 1)

Source of Variation	df	SS	MS	F	P R > F
B	16	2618.46	163.65	2.83	0.0060
V	2	37253.47	18626.73	322.06	0.0001
BV	32	1850.74			
S(BV)	0				
T	2	421658.95	210829.47	2883.37	0.0001
BT	26	3878.41	149.17	2.04	0.0152
VT	4	39702.23	9925.56	135.74	0.0001
BVT	50	3655.96	73.12		
S(BV)T	0				
ϵ	2				
	134	536084.86			

Table 6.6 ANOVA Results for Viscosity (Design No. 1)

Source of Variation	df	SS (10^{10})	MS (10^{8})	F	PR > F
B	16	4.92	30.8	9.41	0.0001
V	2	6.08	34.0	93.05	0.0001
BV	32	7.51	23.4	7.18	0.0001
T	1	4.51	451.0	138.11	0.0001
BT	16	1.35	8.4	2.58	0.0019
VT	2	4.11	206.0	62.93	0.0001
BVT	32				
ϵ	112	3.66	3.27		
	131	35.74			





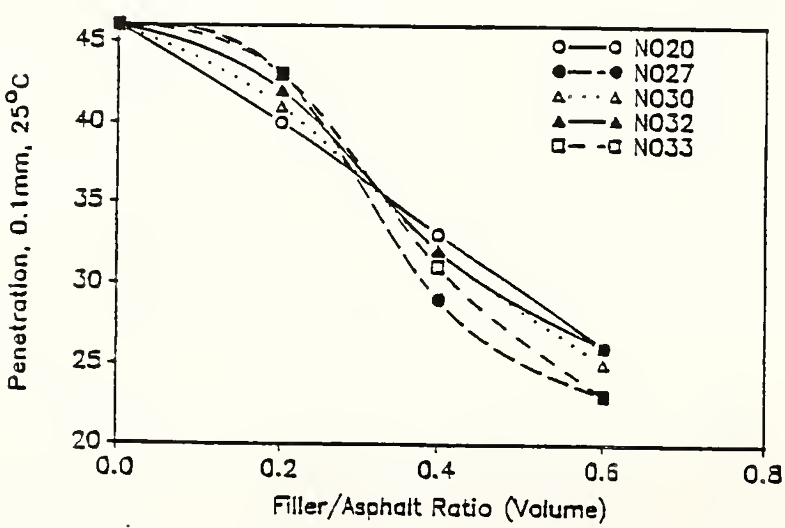


Figure 6.3 Effect of Baghouse Fines Concentration of Penetration of Asphalt Mastics (77°F) (Continue)

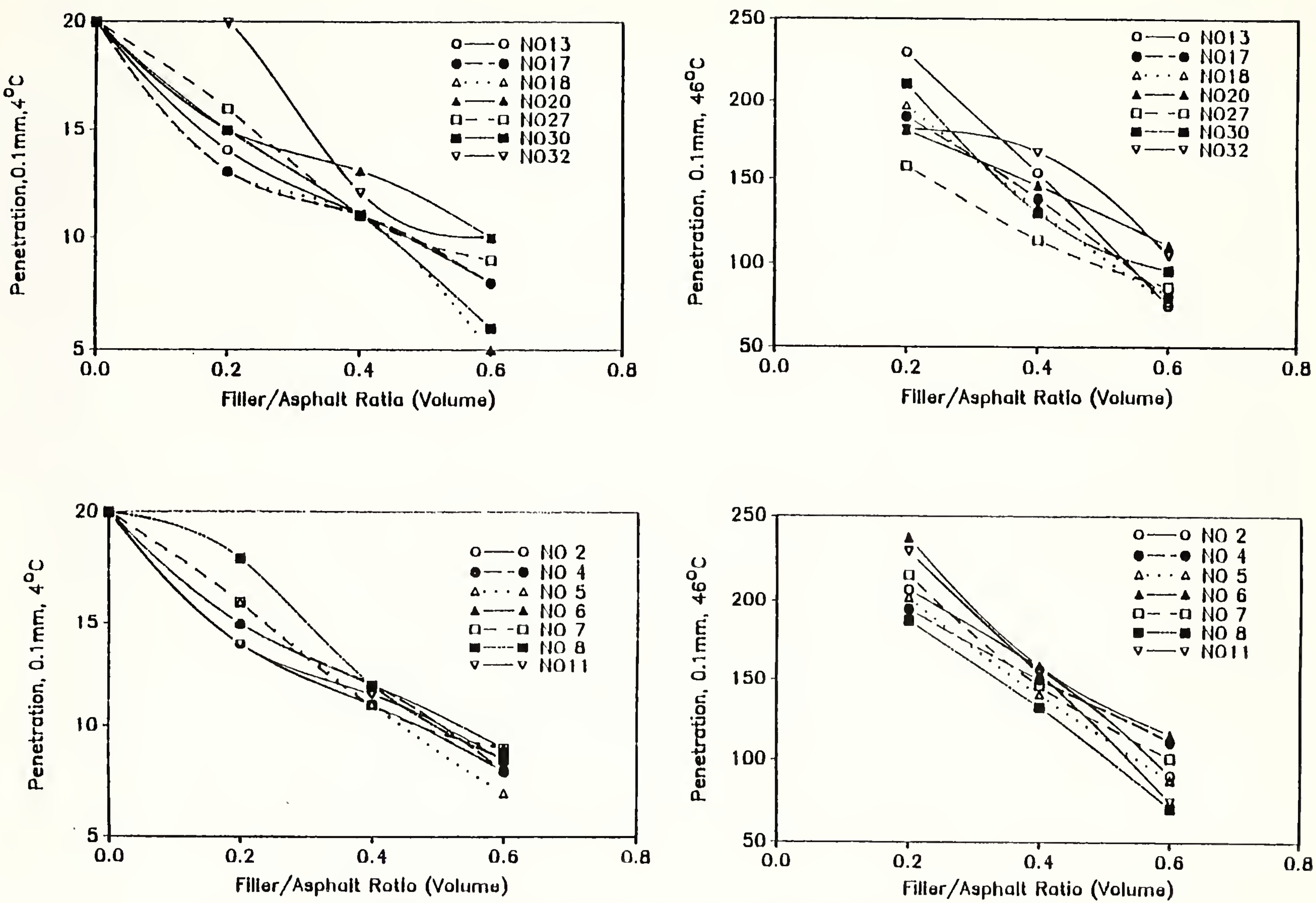


Figure 6.3 Effect of Baghouse Fines Concentration on Penetration of Asphalt Mastics

The following linear model is assumed:

$$Y_{ijkl} = \mu + B_i + V_j + BV_{ij} + T_k + BT_{ik} + VT_{jk} + BVT_{ijk} + \epsilon_{ijkl} \qquad 6.2$$

where Y_{ijkl} = response variable: viscosity

B, V, T, μ = the same as model 6.1

i = 1, 2, ... 17; j = 1, 2, 3; k = 1, 2; l = 1, 2

The ANOVA results shows that the differences among baghouse fines, mineral fillers, fines/asphalt ratio, and temperature are statistically significant at the $\alpha = 0.05$ level. The two way interaction effects are also significant, see Table 6.6.

Figure 6.4 and Figure 6.5 illustrate the effects of the concentration of different fines on the viscosity of asphalt mastics at different temperatures. Figure 6.4 shows such effects at a temperature of 140°F (60°C). Figure 6.5 shows these effects at a temperature of 275°F (135°C). Both figures illustrate that wide variations of asphalt mastics viscosity occur even when the same concentrations of different fines were used. A more than tenfold increase in viscosity is shown for No. 11, No. 13, No. 17 at a high concentration of fines. On the basis of viscosity it may be concluded that surface area and particle size distribution contribute to the increase of the viscosities of fines/asphalt mastics in these tests.

6.2.3 Softening Point and Ductility

The test results of softening point and ductility are also

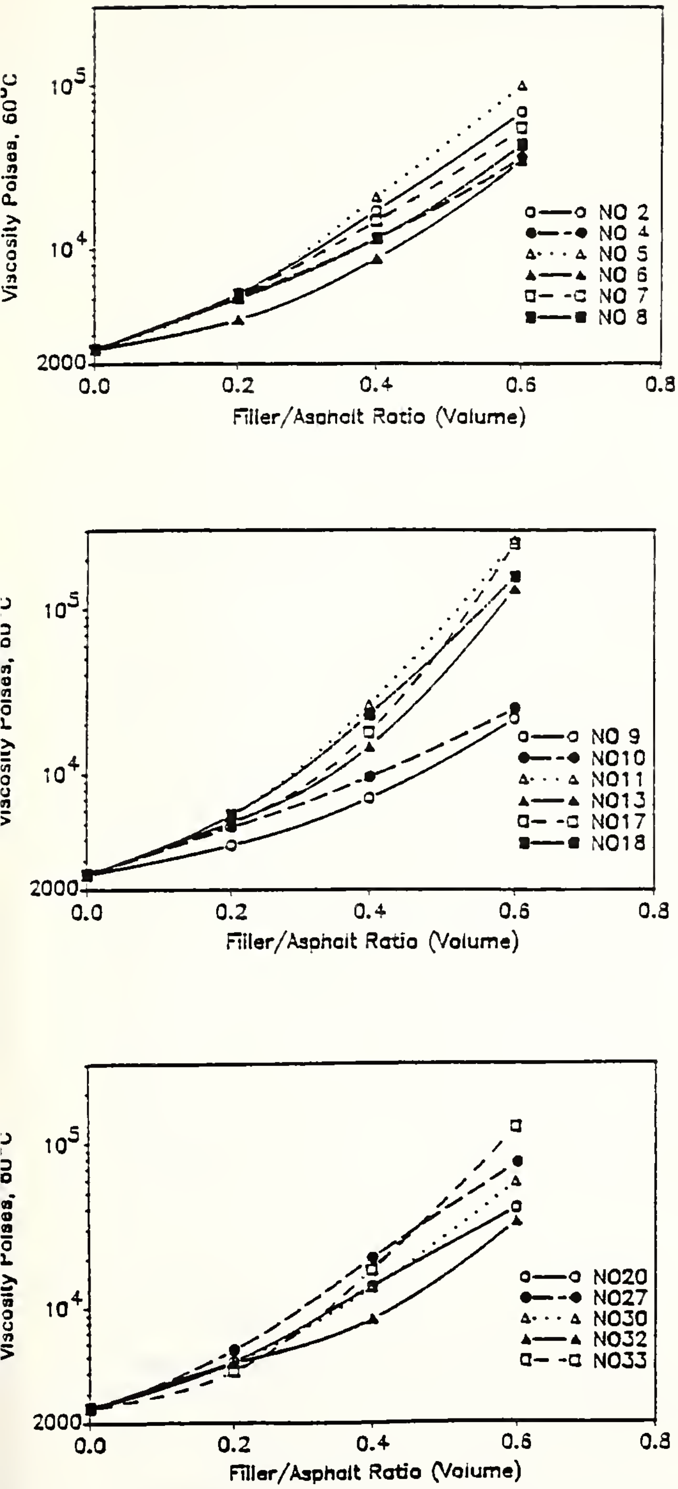


Figure 6.4 Effect of Baghouse Fines Concentration on Viscosity of Asphalt Mastics (140°F)

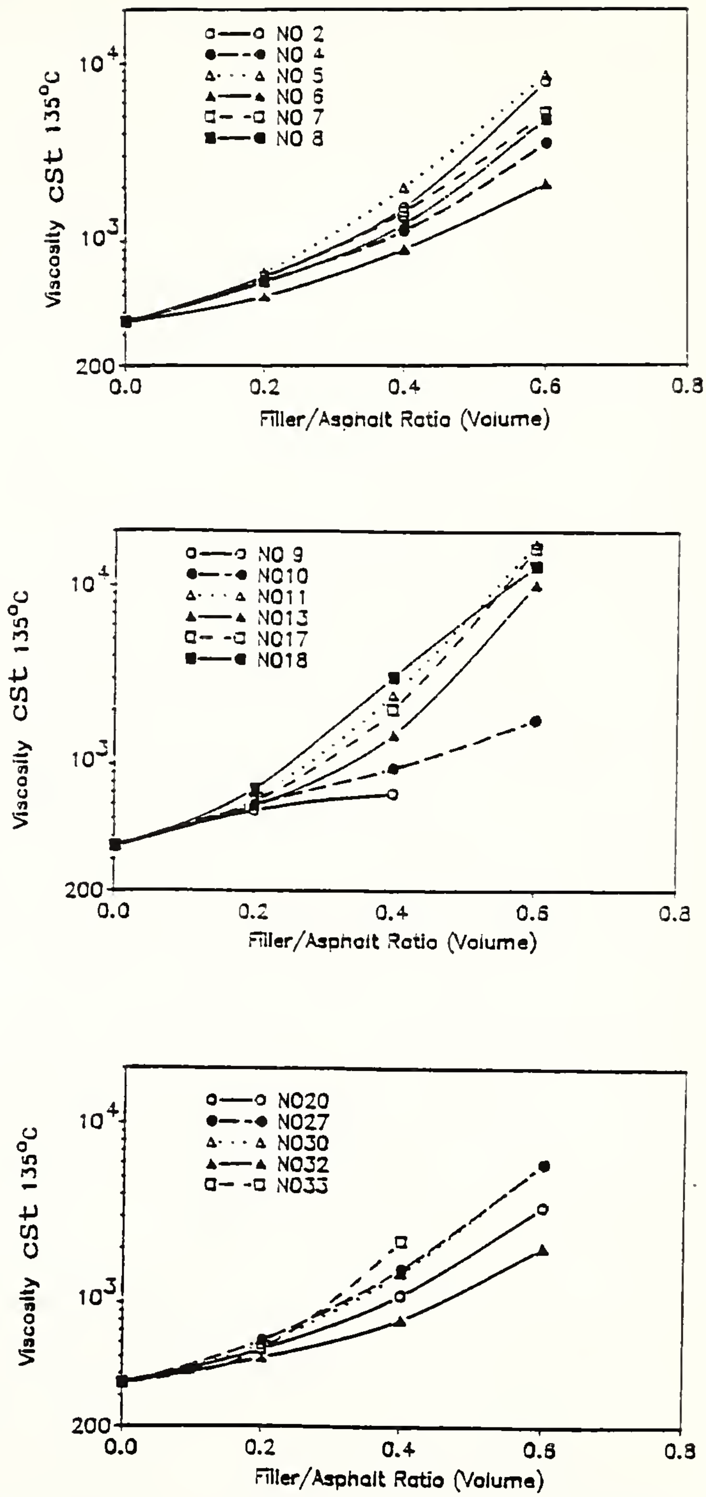


Figure 6.5 Effect of Baghouse Fines Concentration on Viscosity of Asphalt Mastics (275°F)

tabulated in Appendix A-2. The assumed linear model is simpler than 6.1 and 6.2:

$$Y_{ijk} = \mu + B_i + V_j + BV_{ij} + \epsilon_{ijk} \qquad 6.3$$

where Y_{ijk} = response variables, soft point or ductility

B, V, H = the same as model 6.1

i = 1, 2, ... 17; j = 1, 2, 3; k = 1,2

The ANOVA results are shown in Table 6.7 and 6.8. The differences among baghouse fines, mineral fillers, fine/asphalt ratio are significant at $\alpha = 0.05$ level.

Figure 6.6 and 6.7 illustrate the concentration effects of different fine or ductility and softening point. Figure 6.6 indicates that low concentrations of fines reduce the ductility of asphalt mastics. Fines which tend to increase asphalt mastics viscosity to a greater extent also tend to decrease the ductility of asphalt mastics significantly. Softening point versus fines concentration trends for different fines as indicated in Figure 6.7. Fines which increase asphalt mastics viscosity to the greatest extent also increase the softening point of the asphalt mastics more pronouncedly.

Therefore, after examination of the changes in viscosity, penetration, softening point and ductility from pure asphalt cement to mastics, the stiffening, strengthening effects of the filler materials are dramatic. In order to investigate this phenomenon the following indicators of temperature susceptibility were

Table 6.7 ANOVA Results for Softening Point (Design No. 1)

Source of Variation	df	SS	MS	F	PR > F
B	16	745.56	46.57	52.51	0.0001
V	2	3533.34	1766.20	1991.16	0.0001
BV	32	622.66	19.45	21.93	0.0001
ϵ	51	45.25	0.89		
	101	4946.71			

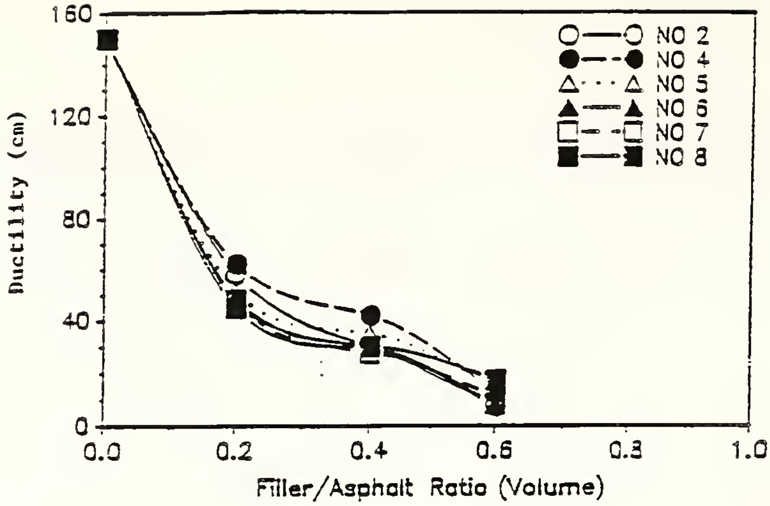
Table 6.8 ANOVA Results for Ductility (Design No. 1)

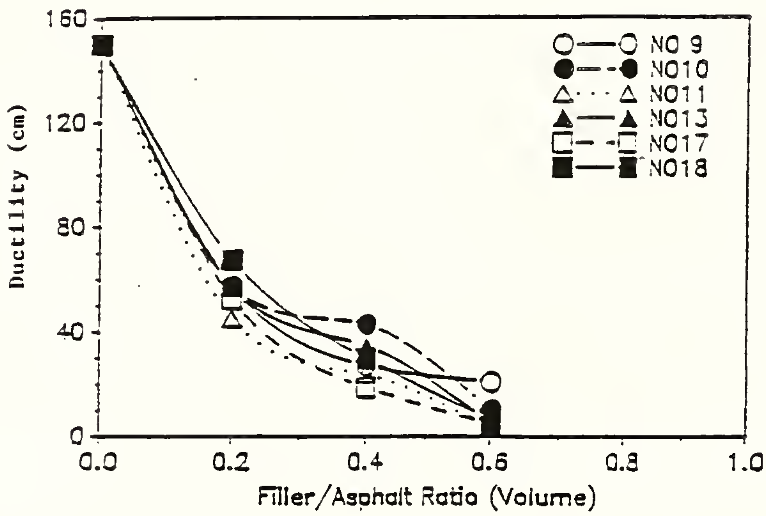
Source of Variation	df	SS	MS	F	PR > F
B	16	3038.56	189.99	2.54	0.0066
V	2	27518.57	13795.46	183.95	0.0001
BV	32	3561.89	111.45	1.49	0.1042
ϵ	48	3590.42	74.80		
	96	38087.58			

Table 6.9 ANOVA Results for Temperature Susceptibility

Source of Variation	Response Variables				
	PI	PVN1	PVN2	PR	VTS
B	S.	S.	S.	N.S.	S.
V	S.	S.	S.	S.	S.

S. = significant at $\alpha = 0.05$, N.S. = not significant at $\alpha = 0.05$





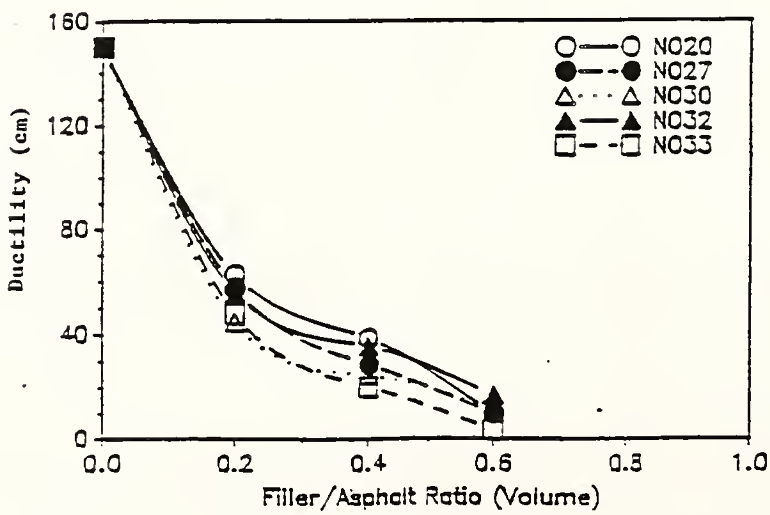
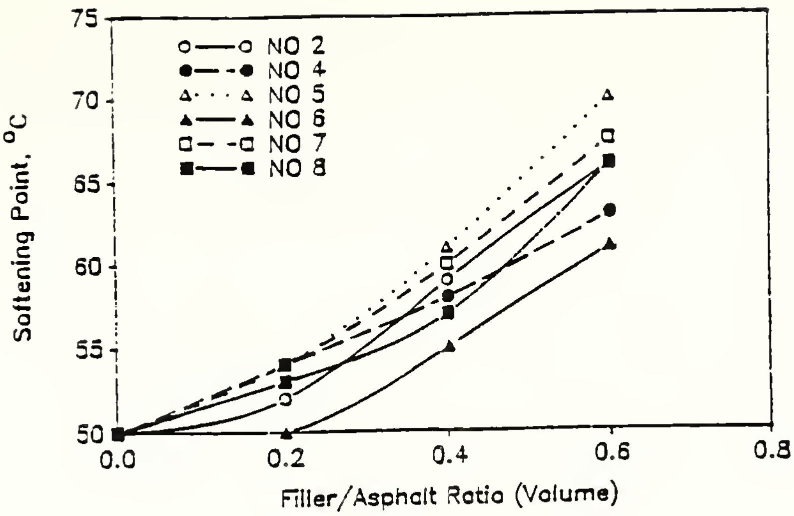
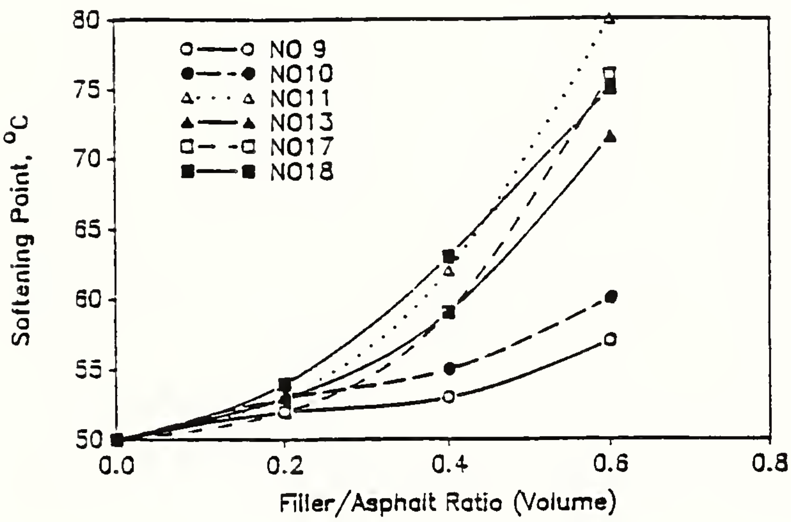


Figure 6.6 Effect of Baghouse Fines Concentration on Ductility of Asphalt Mastics (No. 2-33)





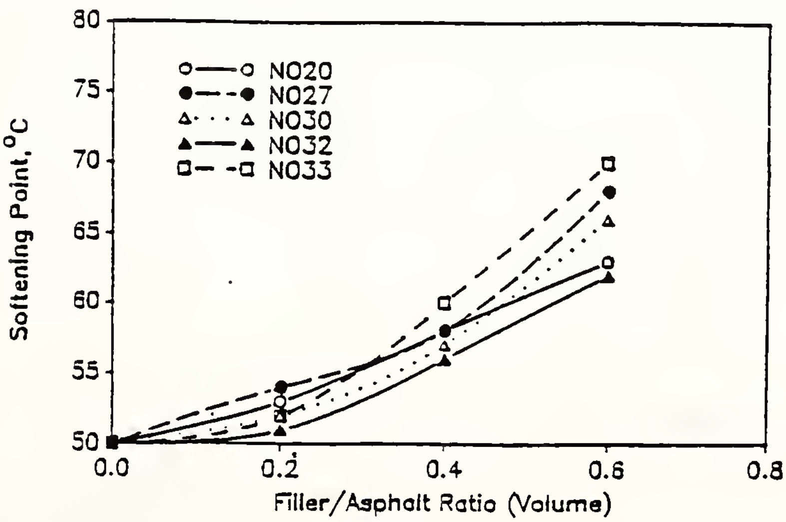


Figure 6.7 Effect of Baghouse Fines Concentration on the Softening Point of Asphalt Mastics (No. 2-33)

calculated:

(i) PI (Penetration Index)

(ii) PVN (Penetration Viscosity Number)

(iii) PR (Penetration Ratio)

(iv) VTS (Viscosity Temperature Susceptibility)

The values of these characteristics and the ANOVA results are given in Appendix A-2 and Table 6.9 respectively. The primary observations from these analyses are presented in the following sections.

6.2.4 PI Temperature Susceptibility

PI temperature susceptibility is an indicator of temperature susceptibility. The PI value requires an asphalt penetration at 77°F (25°C) and a ring-ball softening point temperature for its calculation. The result shows that there are very significant differences for these variables among baghouse fines and concentrations of fines. A larger PI value indicates a lower temperature susceptibility. The PI values of all samples are larger than -1.0, so these samples have low temperature susceptibilities. However the No. 11 asphalt mastic (B/A = 0.6) was found to be stiffer than any others in the test.

Figure 6.8 illustrates the concentration effects of different fines on the PI value of asphalt mastics.

6.2.5 PR Temperature Susceptibility

Penetration ratio is the ratio between the penetrations at

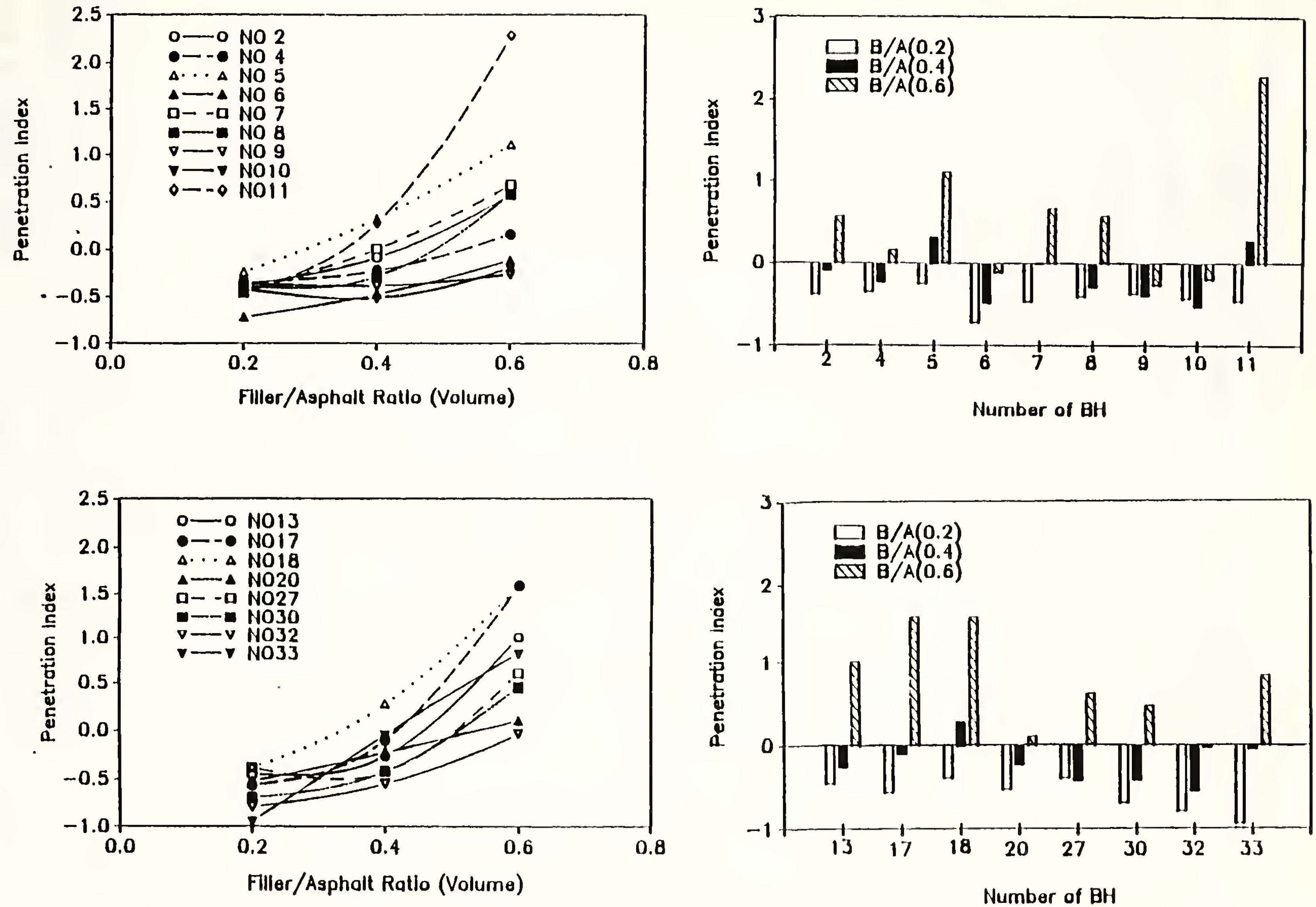


Figure 6.8 Effect of Baghouse Fines Concentration on the Penetration Index of Asphalt Mastics (No. 2-33)

39.2°F (4°C) and 77°F (25°C). This variable is an indicator of temperature susceptibility in the temperature range from 39.2°F to 77°F. The ANOVA shows that there are also very significant differences in these variables for different baghouse fines at different concentrations. There is a trend for a decrease in penetration ratio with increasing concentration of baghouse fines. However, this pattern is not observed for No. 11 and No. 13 asphalt mastics. Figure 6.9 illustrates the concentration effects of different fines on PR value of asphalt mastics.

6.2.6 VTS Temperature Susceptibility

Viscosity temperature susceptibility is an indicator of temperature susceptibility in the temperature range from 140°F (60°C) to 275°F (135°C). The ANOVA shows that there are very significant differences in the main factors such as baghouse fines and concentrations. There is also a trend for a decrease in VTS value with increasing concentration of baghouse fines. However, No. 6 and No. 30 were found to be more temperature susceptible than other asphalt mastics in this temperature range. Figure 6.10 illustrates the concentration effects of different fines on VTS value of different asphalt mastics.

6.2.7 PVN Temperature Susceptibility

There are two kinds of PVN values, one is calculated from viscosity at 275°F (135°C) and penetration at 77°F (25°C), the other is calculated from viscosity at 140°F (60°C). This variable is an

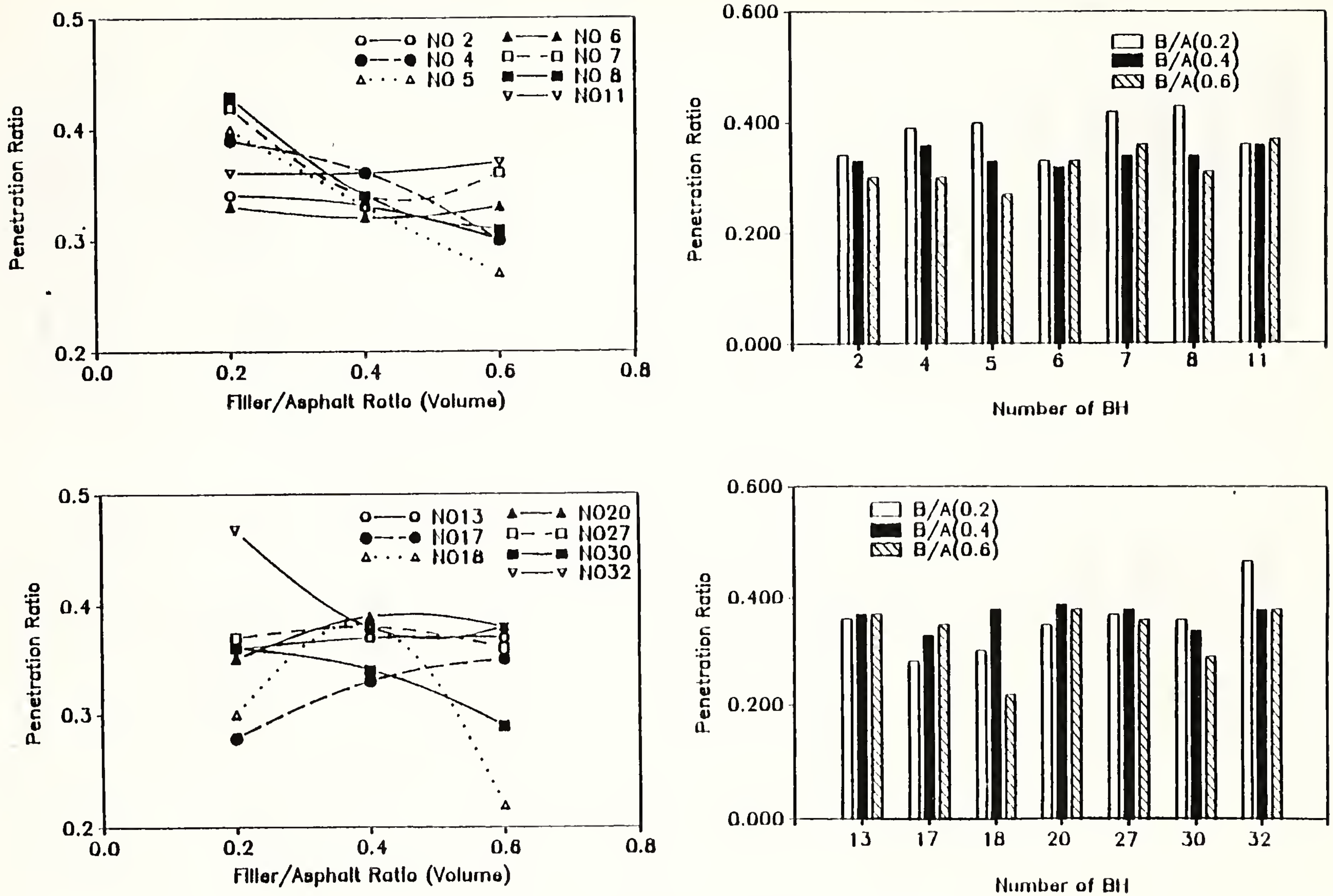


Figure 6.9 Effect of Baghouse Fines Concentration on the Penetration Ratio of Asphalt Mastics (No. 2-33)

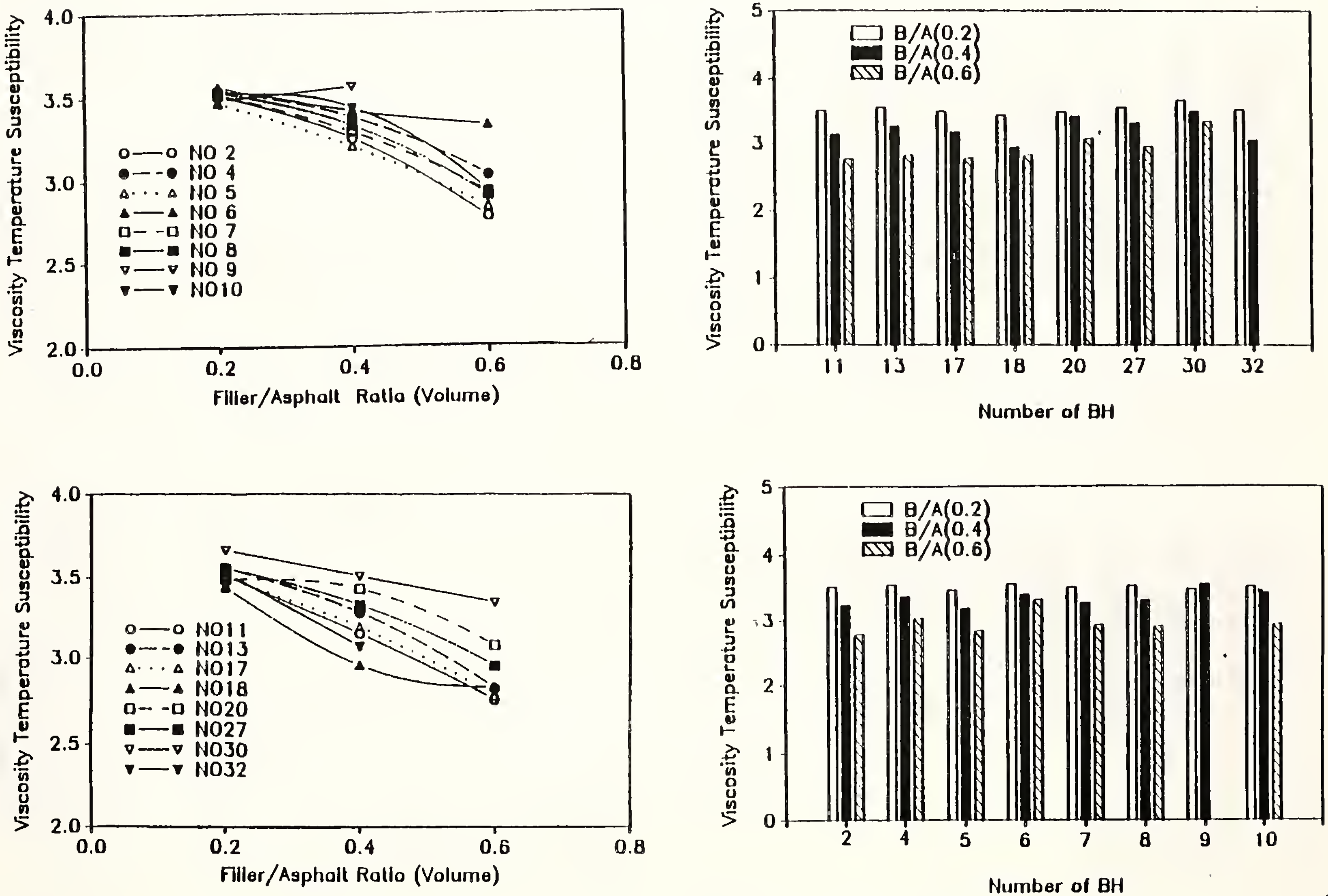


Figure 6.10 Effect of Baghouse Fines Concentration on the Viscosity Temperature Susceptibility (No. 2-33) (77°F-275°F)

indicator of temperature susceptibility in the range of 77°F to 275°F or 77°F to 140°F. The ANOVA shows that different baghouse fines and concentrations are very significant. Data in Appendix A-2 and Figure 6.11 indicate that the effect of baghouse fines in PVN at 275°F (135°C) or 140°F (60°C) are very similar to PI values shown in Figure 6.8. No. 2, 5, 11, 13, 17, and 18 asphalt mastics (B/A = 0.6) were found to have higher PVN values and to be stiffer than others in this temperature range.

6.3 Summary of Results

Although the extent of the testing accomplished using these baghouse fines and mineral fillers was limited, the findings presented in this chapter may be summarized. These are listed below.

6.3.1 Characteristics of Baghouse Fines and Mineral Fillers

1. The specific gravity, particle size distribution, surface area and PH value, although obtained from standard tests, contribute to an understanding of the nature of baghouse fines and mineral fillers. The results of these tests need to be considered in asphalt paving mixtures design procedure.
2. The void contents by the dry compaction method appears to offer a good reference as far as characterizing the baghouse fines material. According to their capacity to occupy the bulk volume in the presence of asphalt cement,

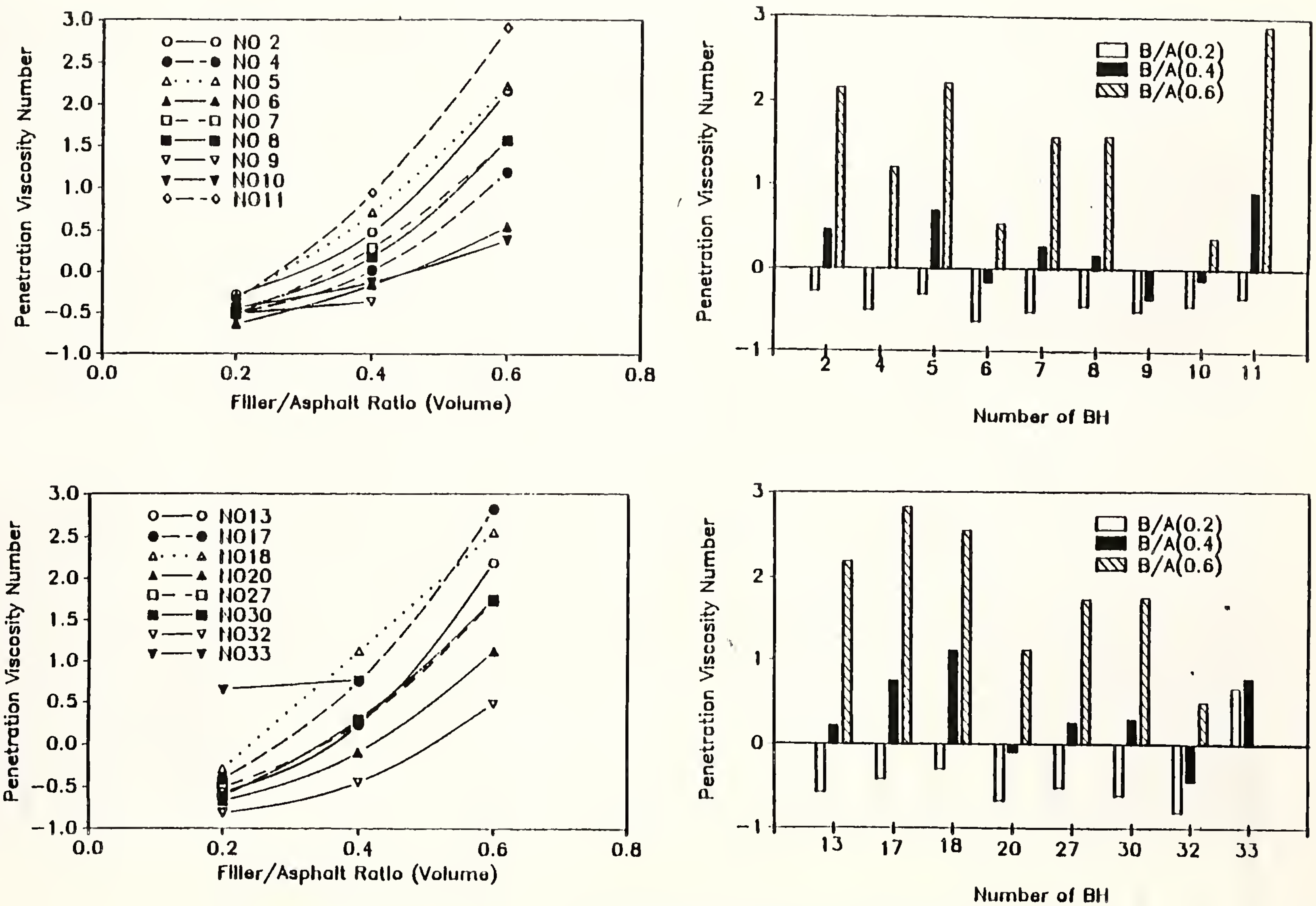


Figure 6.11 Effect of Baghouse Fines Concentration on the Penetration Viscosity Susceptibility (No. 2-33) (140°F-275°F)

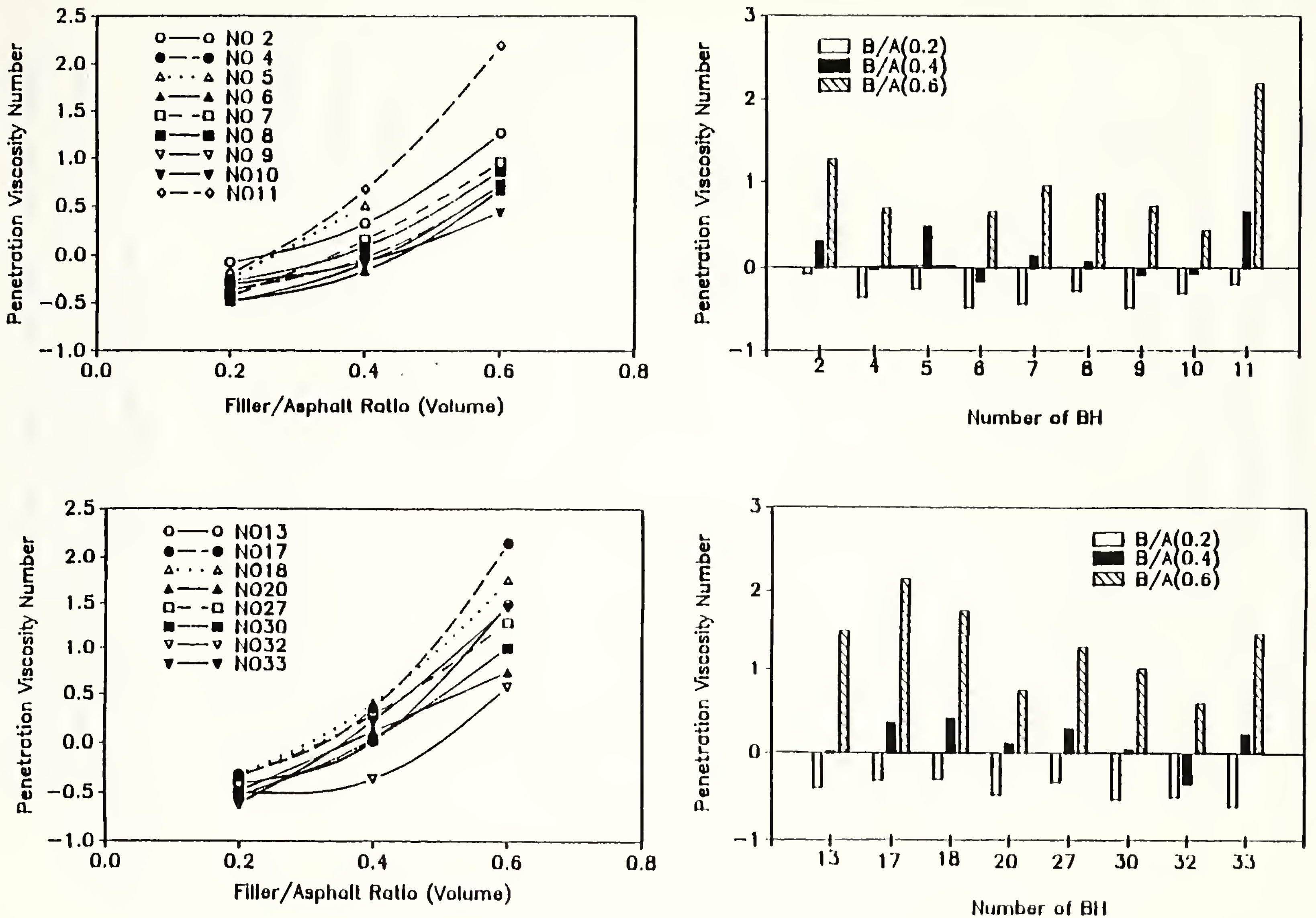


Figure 6.11 Effect of Baghouse Fines Concentration on the Penetration Viscosity Susceptibility (No. 2-33) (77°F-275°F)

one can define % V_{fB}, the percent bulk volume of fines, to describe the effect of bulk volume of fines on rheological properties of asphalt mastics. Basic test results are contained in Figure 6.12 and 6.13. These semi-log plots indicate that the viscosities continue to increase rapidly as the bulk volume of fines is increased. These figures show pronouncedly viscosity ratio increases between 60 to 80 percent bulk volume of fines, especially between the 70 to 80 percent range. Figure 6.14 illustrates a similar trend for a plot of bulk volume of fines versus increase in softening point temperature.

3. Parameters developed from the simple dry compaction method to get the void content in baghouse fines, such as B/A, V_{fa}, and % V_{fB} appear to be useful for correlation with consistency tests such as penetration, viscosity, ductility, and softening point which indicate the stiffening effects of baghouse fines in asphalt mastics.
4. There appears to be a tendency for some baghouse fines to significantly increase the stiffening of asphalt mastics. This trend needs to be evaluated further in consideration of designing mineral fillers for asphalt paving mixtures.

6.3.2 Characteristics of Fines/Asphalt Mastics

1. The penetration, ductility, and the ring and ball softening point tests were observed to be useful for

demonstrating the characteristics of asphalt mastics.

2. In view of ANOVA, the significance ($\alpha = 0.05$) of the behavior of asphalt mastics is a function of different types and concentrations of baghouse fines. Asphalt mastics No. 11 and No. 17 appear to be significantly different when compared to the other asphalt mastics on the basis of viscosity and penetration.

3. The relationship between viscosity at 60°C, concentrations, and different type of baghouses can be defined by a linear model.

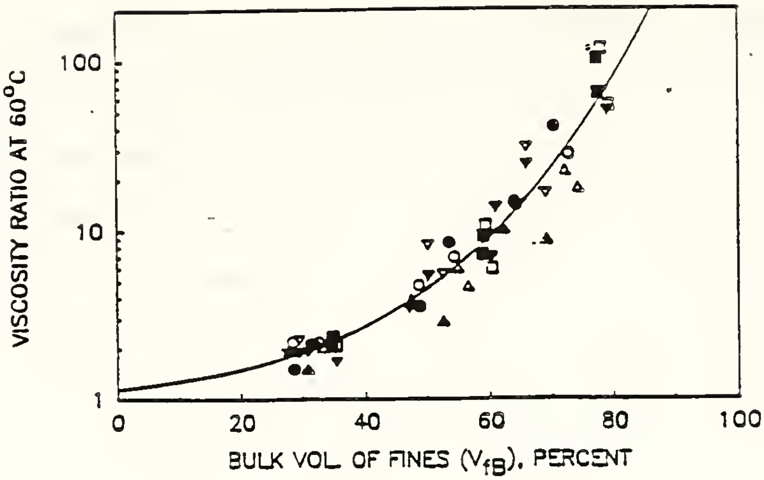


Figure 6.12 % V_{fb} Versus log Viscosity at 140°F

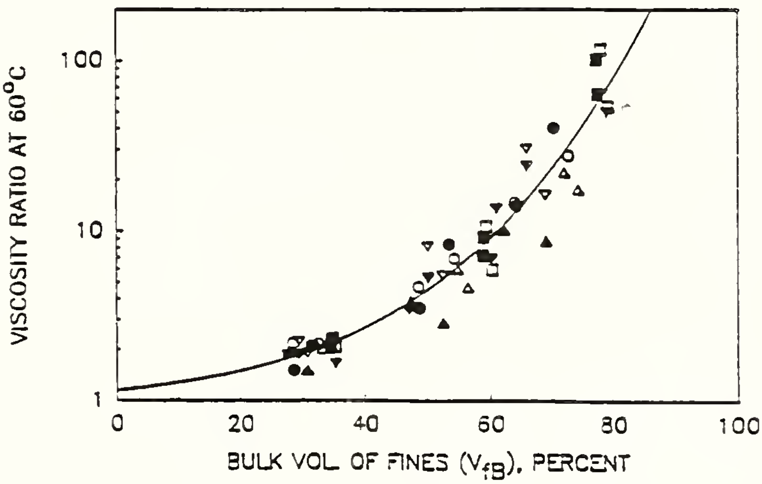


Figure 6.13 % V_{fb} Versus log Viscosity at 275°F

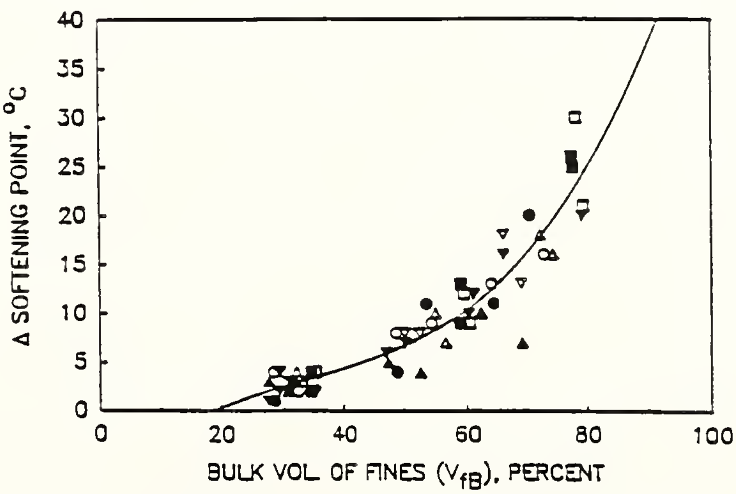


Figure 6.14 % V_{fb} Versus Δ SF

CHAPTER 7

ASPHALT PAVING MIXTURES WITH BAGHOUSE FINES

7.1 Introduction

An experimental design to assess the effects of different baghouse fines on asphalt paving mixtures using the gyratory testing machine, resilient modulus test apparatus and indirect tensile test equipment was devised and performed. The general laboratory procedures described in Chapter 4 were used to prepare and to test the gyratory compacted specimens.

The main objectives of the experiment were as follows:

1. The gyratory testing machine was used for determining the maximum permissible bitumen content consistent with intensity of traffic load as simulated in laboratory.

2. Indirect tensile and resilient modulus tests were performed to evaluate the effects of asphalt paving mixtures containing baghouse fines on the tensile strength and resilient modulus.

3. The rutting potential and the mix stiffness were evaluated.

4. A statistical analysis was conducted to establish the significance and relationships between test parameters. This was done by performing analysis of variance and regression analysis.

The independent variables included the different types of baghouse fines, the percent of baghouse fines added, the percent asphalt cement added and the compactive effort. Gyratory parameters were obtained during the compaction process. The properties of the paving mixtures measured at various temperatures were the resilient modulus, the Hveem stability, the indirect tensile strength, and mix stiffness.

7.2 Method of Analysis

The response variables were analyzed with the aid of the Analysis of Variance statistical method. The ANOVA determined whether the effects of certain factors and/or interactions of factors were statistically significant.

In most ANOVA problems the assumption which was historically thought to have been most critical was homogeneous variances. The assumption of homogeneity of variance was checked by using the Bartlett's Test (38). If the Bartlett's test value was less than the critical value at d=0.001, the assumption of homogeneity of variance would be accepted. If it was rejected, the data should be transformed in order for the ANOVA to produce meaningful results.

ANOVA and Bartlett's test statistical package programs were available on the IBM 3090 at the Purdue University Computing Center.

The general statistical model for the gyratory parameters of the resilient modulus in design No. 2 is shown below:

$$\begin{aligned} Y_{ijklmn} = \ & \mu + B_i + \delta_{(i)} + P_j + BP_{ij} + A_k + BA_{ik} + PA_{jk} + BPA_{ijk} + \\ & S(BPA)_{(ijk)l} + w_{ijkl} + C_m + BC_{im} + PC_{jm} + BPC_{ijm} + AC_{km} + \\ & BAC_{ikm} + PAC_{jkm} + BPAC_{ijkm} + S(BPA)C_{(ijk)lm} + v_{ijklm} + T_n + \\ & + \epsilon_{ijklmn} \quad \text{------------------------------} 7.1 \end{aligned}$$

Where Y_{ijklmn} = Response variable: GEPI, GSI, GCI, M_R, ITS, S, and J(t)

μ = Overall mean of response variable

B_i = Effect of different types of baghouse fines

P_j = Effect of the percent of baghouse fines added

A_k = Effect of percent of asphalt cement added

C_l = Effect of compactive effort

T_m = Effect of testing temperature

$S(BPA)_{(ijkl)l}$ = Within error of BPA combination

δ, w, v = Restriction errors

ϵ = Experimental error

BP_{ij} BA_{ik}.....$BPACT_{ijkmn}$ = Effect of interactions of factors i,j,k,n = 1,2,3   l = 1,2   m = 1,2,3,4

The model followed the split-split plot experimental design. The first restriction error, δ, was due to the fact that the specimens were fabricated on different days. The second error, w, was due to the fact that readings were taken from the same specimen at the various revolutions. The third error, v, was due to the fact that readings were taken from the same specimen at the various testing temperatures.

This general model included all the factors, interaction terms and error terms. Design No. 2 was a complete representation of the response and independent variables.

7.3 Results

The gyratory parameters are tabulated in Appendix B-1. Test results include data on each replicate tested as well as the average of the two replicates tested.

Results of the resilient modulus test with respect to the different type of baghouse fines, percent of baghouse fines, percent of asphalt cement and test temperature have been tabulated in Appendix B-2. Test results cover data on each replicate tested, and average values of modulus along two directions in which the specimens were tested.

Computed values of mix stiffness, indirect tensile stress, total tensile strain at failure, and Hveem stability are presented in Appendix B-3. Test results include data on each replicate tested as well as the average of the test.

7.4 Analysis of Results

7.4.1 Gyratory Parameters

The gyratory parameters for the asphalt paving mixtures containing baghouse fines were recorded during the compaction process. ANOVAs were performed on the obtained data using the following model:

$$Y_{ijkl} = \mu + B_i + \delta_{(i)} + P_j + A_k + PA_{jk} + BP_{ij} + BA_{ik} + BPA_{ijk} + \epsilon_{ijkl} \quad \text{--7.2}$$

This is a complete randomized factorial design. The terms in the model were defined earlier. The ANOVA results are presented in Table 7.1.

Figure 7.1 depicts the gyratory indices as functions of

Table 7-1 ANOVA Results for Gyratory Parameters

Source of Variation	GEPI	Response GCI	Variables GSI	rd
B	S.*	N.S.	S.	S.
P	S.	N.S.	S.	N.S.
A	S.	N.S.	S.	N.S.
BP	S.	N.S.	N.S.	S.
BA	N.S.	N.S.	S.	N.S.
PA	N.S.	N.S.	S.	N.S.
BPA	N.S.	N.S.	N.S.	N.S.

S.* = Significant at $\alpha = 0.10$

S. = Significant at $\alpha = 0.05$

N.S = Not significant at $\alpha = 0.05$

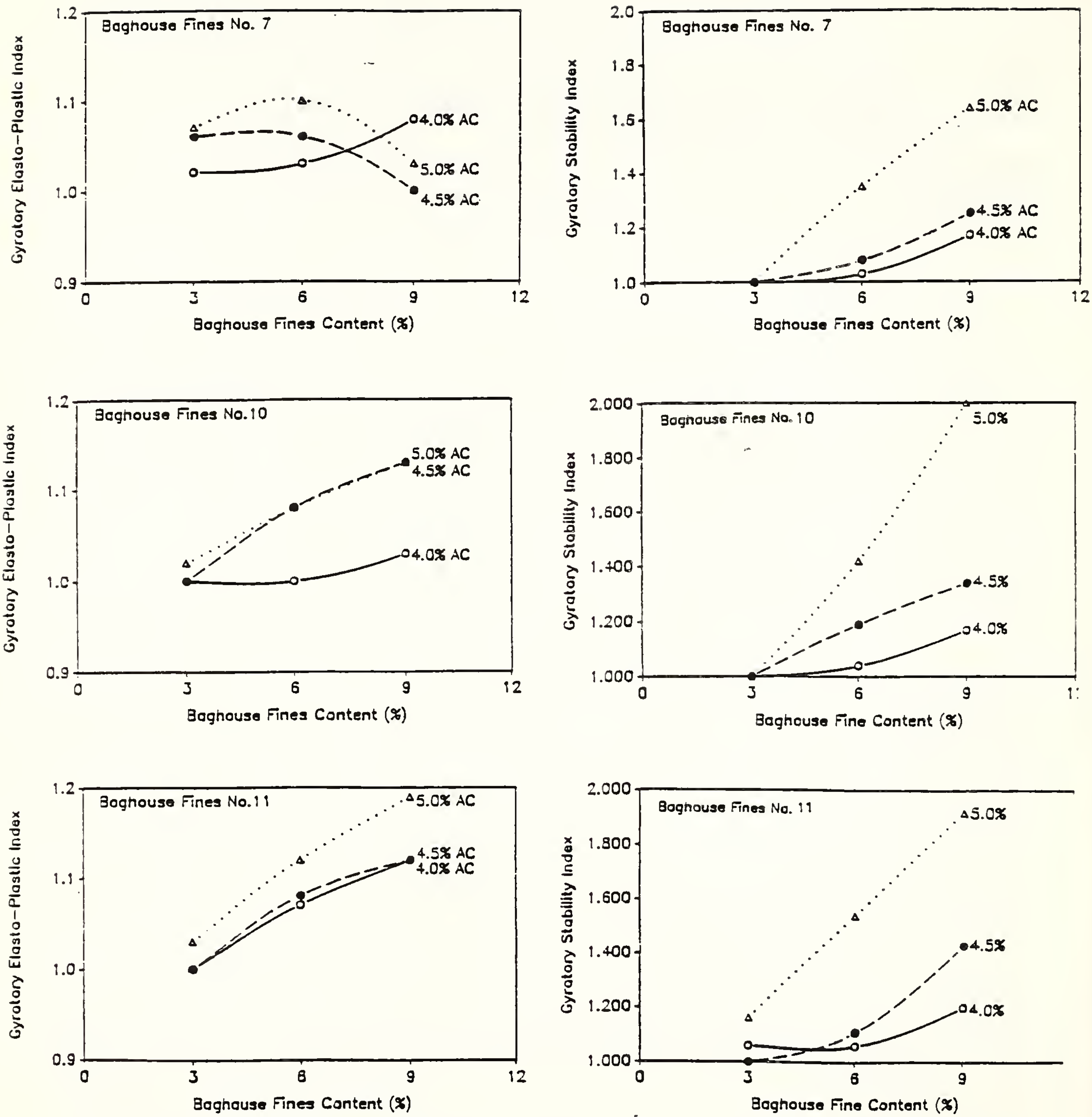


Figure 7.1 Gyratory Indices of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 2) (Continued)

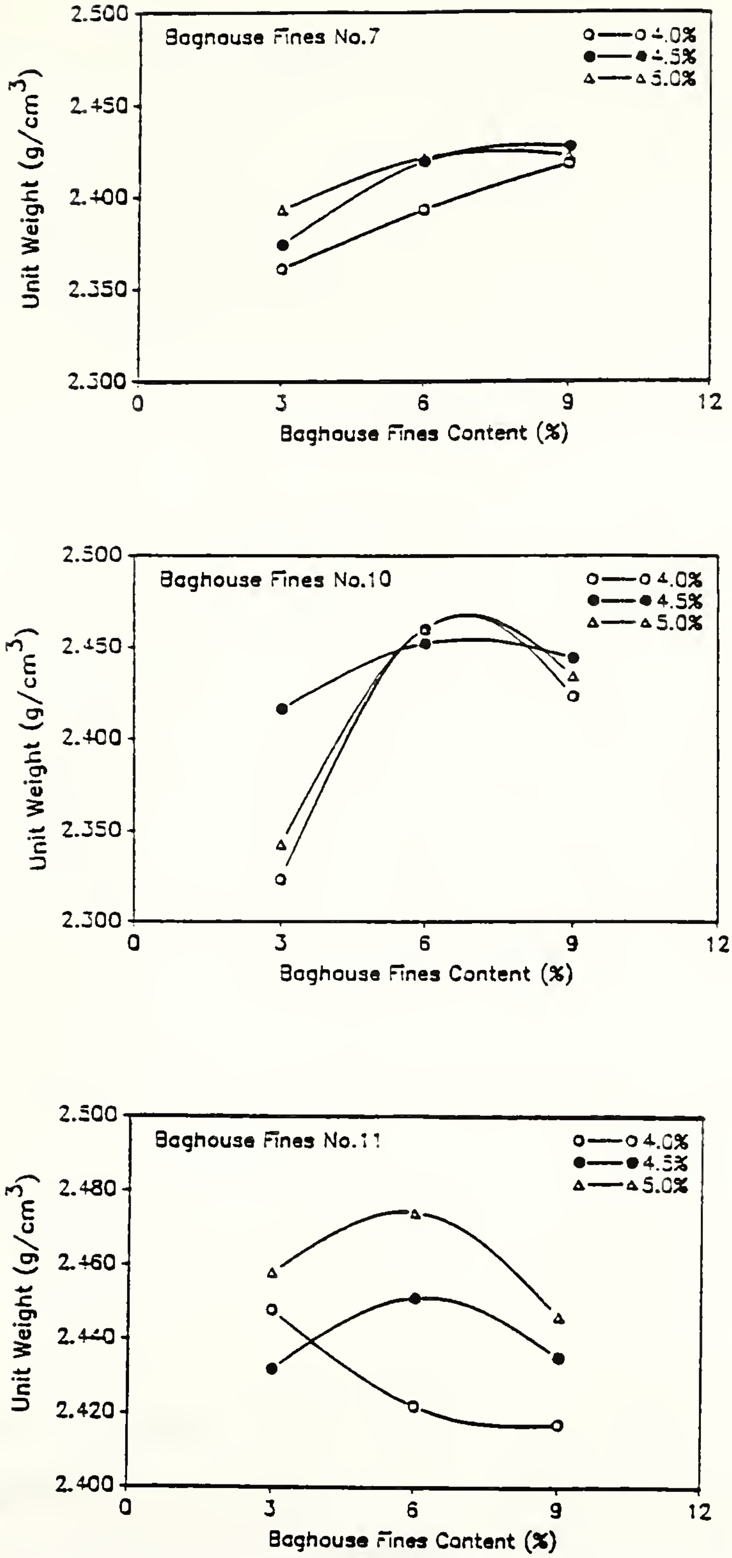


Figure 7.1 Gyratory Indices of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 2)

asphalt content and baghouse fines content. It can be noted that the gyratory compactibility index was insensitive to the change in percent of asphalt cement and baghouse fines added. The gyratory stability index (GSI) remained relatively constant for less than 3% baghouse fines added and increased drastically as the percent of asphalt cement increased from 4.5% to 5.0% and the amount of baghouse fines became greater than 6%.

7.4.2 Resilient Modulus

The resilient modulus values of the asphalt paving mixtures containing baghouse fines as outlined in Design No. 2 are presented in Figure 7.2 as a function of percent of baghouse fines, asphalt content, and type of baghouse fines. It can be observed that the resilient modulus at higher baghouse fines content decreased significantly as asphalt content increased from 4.0% to 5.0%. It can be also be observed that resilient modulus at lower baghouse fines content had a peak value at an asphalt content of 4.5%. This phenomenon appeared to be similar to the usual asphalt paving mixtures design.

ANOVA were performed on the resilient modulus data using the following statistical model:

$$Y_{ijklm} = \mu + B_i + P_j + BP_{ij} + A_k + BA_{ik} + PA_{jk} + BPA_{ijk} + S(BPA)_{(ijk)l} + W_{(ijk)l} + T_m + BT_{im} + PT_{jm} + BPT_{ijm} + AT_{km} + BAT_{ikm} + PAT_{jkm} + BPAT_{ijkm} + S(BPA)T_{(ijk)lm} + \epsilon_{ijklm} \quad \text{------------------7.3}$$

Table 7.2 ANOVA Results for Resilient Modulus

Source of Variation	DF	SS (10^{10})	F	PR>F
B	2	1.21	2.61	0.0837
P	2	6.59	12.19	0.0002
A	2	11.86	21.94	0.0001
BP	4	8.21	7.60	0.0004
BA	4	9.49	0.88	0.4912
PA	4	3.84	3.24	0.0200
BPA	8	1.17	0.54	0.8133
S(BPA)	25	6.76		
T	2	2511.00	5397.40	0.0001
BT	4	6.18	6.84	0.0001
PT	4	6.13	6.58	0.0002
AT	4	8.97	9.64	0.0002
BPT	8	9.74	5.23	0.0001
BAT	8	3.91	2.10	0.0001
PAT	8	2.17	0.78	0.0532
BPAT	16	2.89	2.69	0.7039
TS(BPT)	50	11.64		
	155	2604.89		

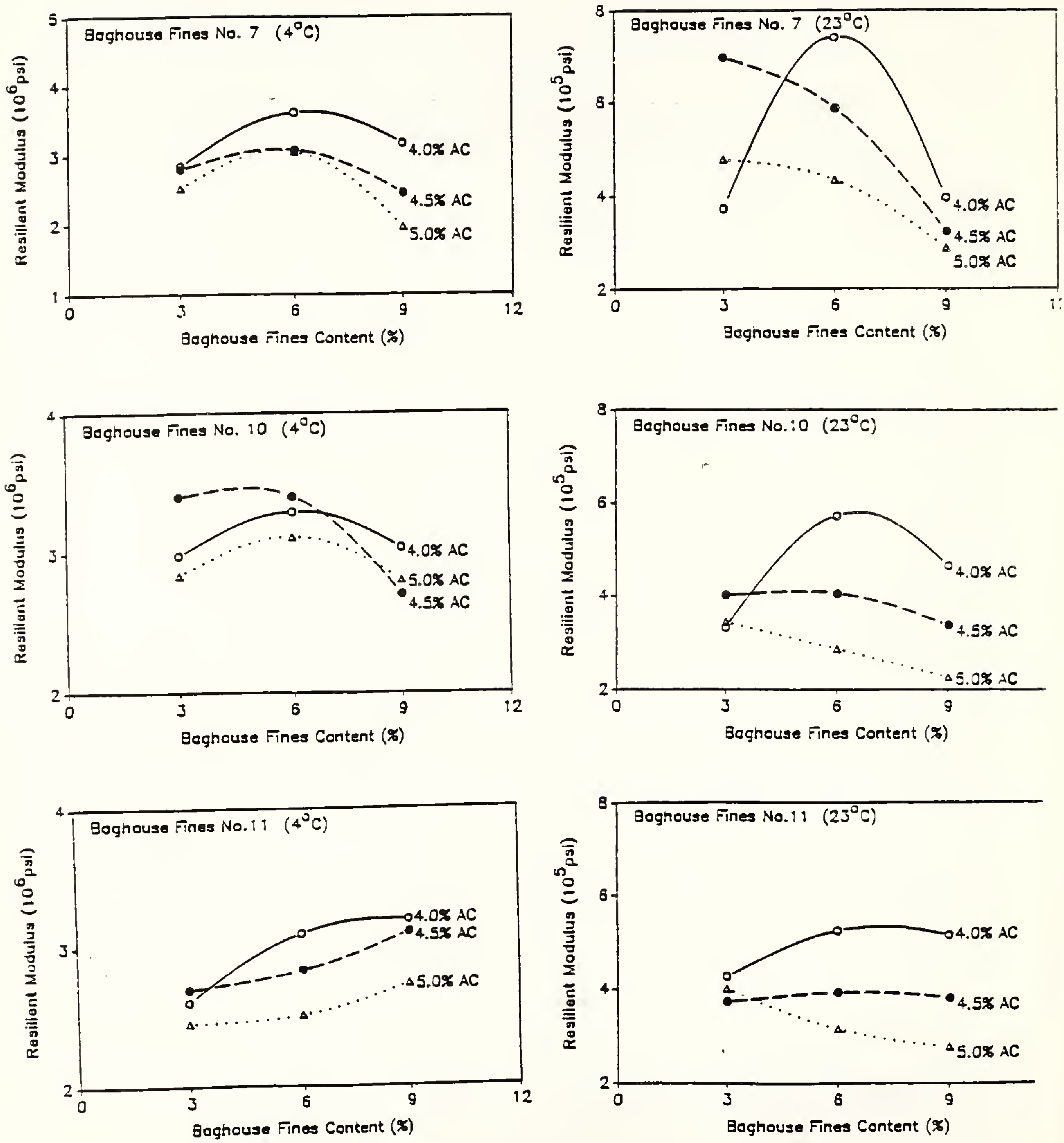


Figure 7.2 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 2) (Continued)

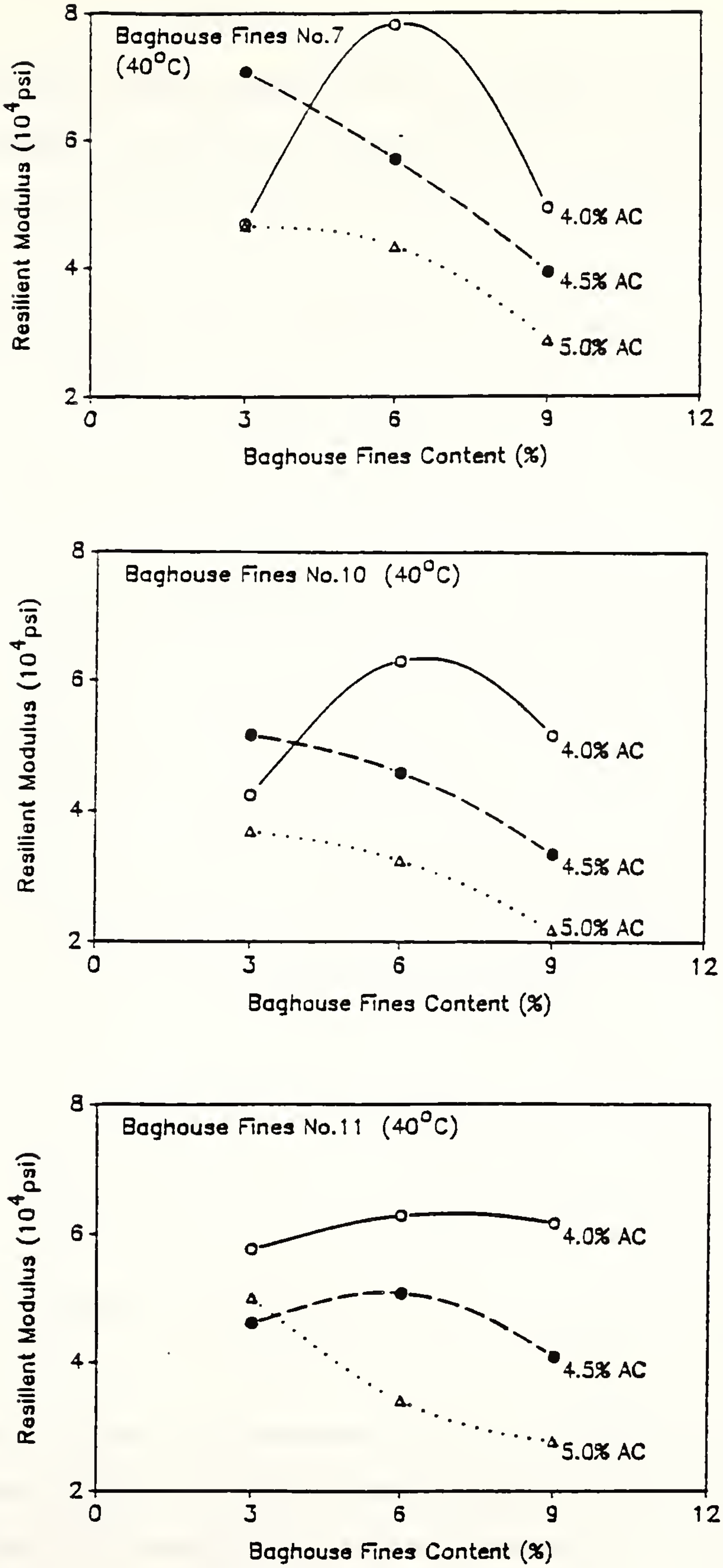


Figure 7.2 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 2)

The model is similar to the general model described in the previous section 7.2, with the exception that the compactive effort terms were not considered. The results of ANOVA are presented in Table 7.2.

The ANOVA results, indicate that the effects of baghouse fines (B), percent of baghouse fines (P), asphalt cement content (A) and testing temperature (T) were all significant . The interaction terms BP, BA, BT, PT, AT, BPT, BAT, PAT were also significant.

7.4.3 Indirect Tensile Strength and Hveem Stability

The test results as tabulated in Appendix B-3 were analyzed as a factorial experiment comprising three types of baghouse fines, three concentrations of baghouse fines, and three different asphalt cement contents. Baghouse fines, percent of baghouse fines, percent of asphalt content were regarded as fixed effects, since in this study limited concern is only in the chosen baghouse fines and asphalt cement content. The experiment has 52 treatment combinations.

The following linear model is assumed for any single measurement in the experiment:

$$Y_{ijkl} = \mu + B_i + P_j + A_k + PA_{jk} + BP_{ij} + BA_{ik} + BPA_{ijk} + \epsilon_{ijkl} \text{----} 7.4$$

This is also a complete randomized factorial design. The ANOVA results are presented in Table 7.3 The ANOVA results (Table 7.3) and Figure 7.3 indicate that the percent of baghouse fines

Table 7.3 ANOVA Results for Indirect Tensile Strength (Continuous)

Source of Variation	df	SS	MS	F	PR>F
B	2	1293.99	646.99	2.15	0.1383
P	2	7487.76	3743.88	12.45	0.0002
A	2	17985.29	8991.15	29.90	0.0001
BP	4	3633.94	980.49	3.02	0.0376
BA	4	1245.96	311.49	1.04	0.4093
PA	4	14751.47	3777.68	12.56	0.0001
BPA	8	5042.52	631.62	2.10	0.0771
ϵ	24	7218.50	300.77		
	50	63742.62			

Table 7.3 ANOVA Results for Indirect Tensile Strength (Failure Tensile Strain)

Source of Variation	df	SS	MS	F	PR>F
B	2	4.21	2.11	7.92	0.0003
P	2	2.54	1.27	4.78	0.0179
A	2	13.01	6.51	24.51	0.0001
BP	4	6.59	1.64	6.20	0.0014
BA	4	1.06	0.265	1.00	0.4269
PA	4	0.86	0.215	0.81	0.5311
BPA	8	15.17	1.90	7.14	0.0001
ϵ	24	6.38	0.266		
	50	50.48			

Table 7.4 ANOVA Results for Hveem Stability

Source of Variation	df	SS	MS	F	PR>F
B	2	224.23	112.17	2.37	0.1150
P	2	2533.50	1266.8	26.77	0.0001
A	2	5322.44	2661.22	56.23	0.0001
BP	4	150.50	37.63	0.800	0.5401
BA	4	210.72	52.68	1.11	0.3934
PA	4	1603.22	400.81	8.47	0.0002
BPA	8	720.99	90.12	1.90	0.1063
ϵ	24	1135.76	47.32		
	50	12558.34			

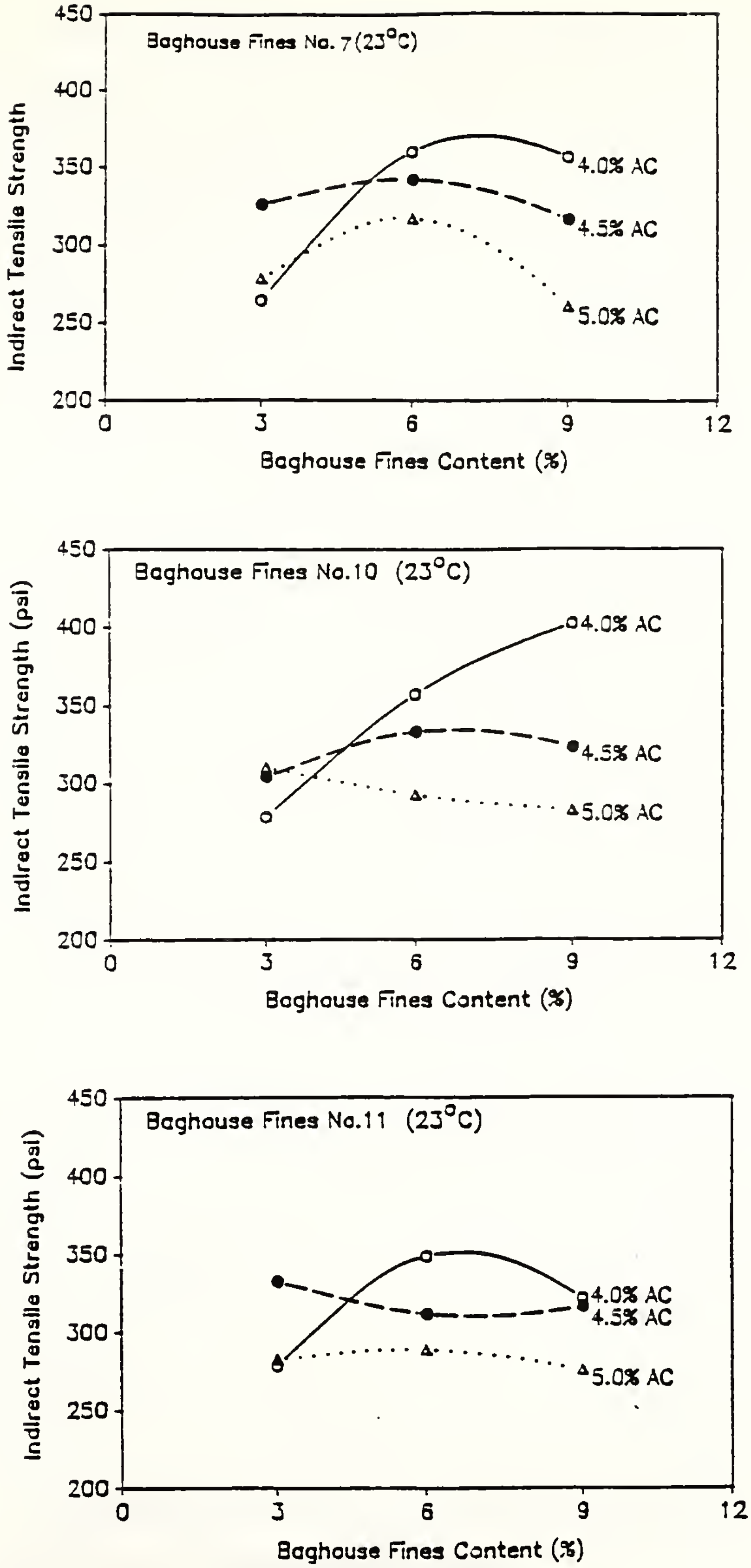


Figure 7.3 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Baghouse Fines (No. 2)

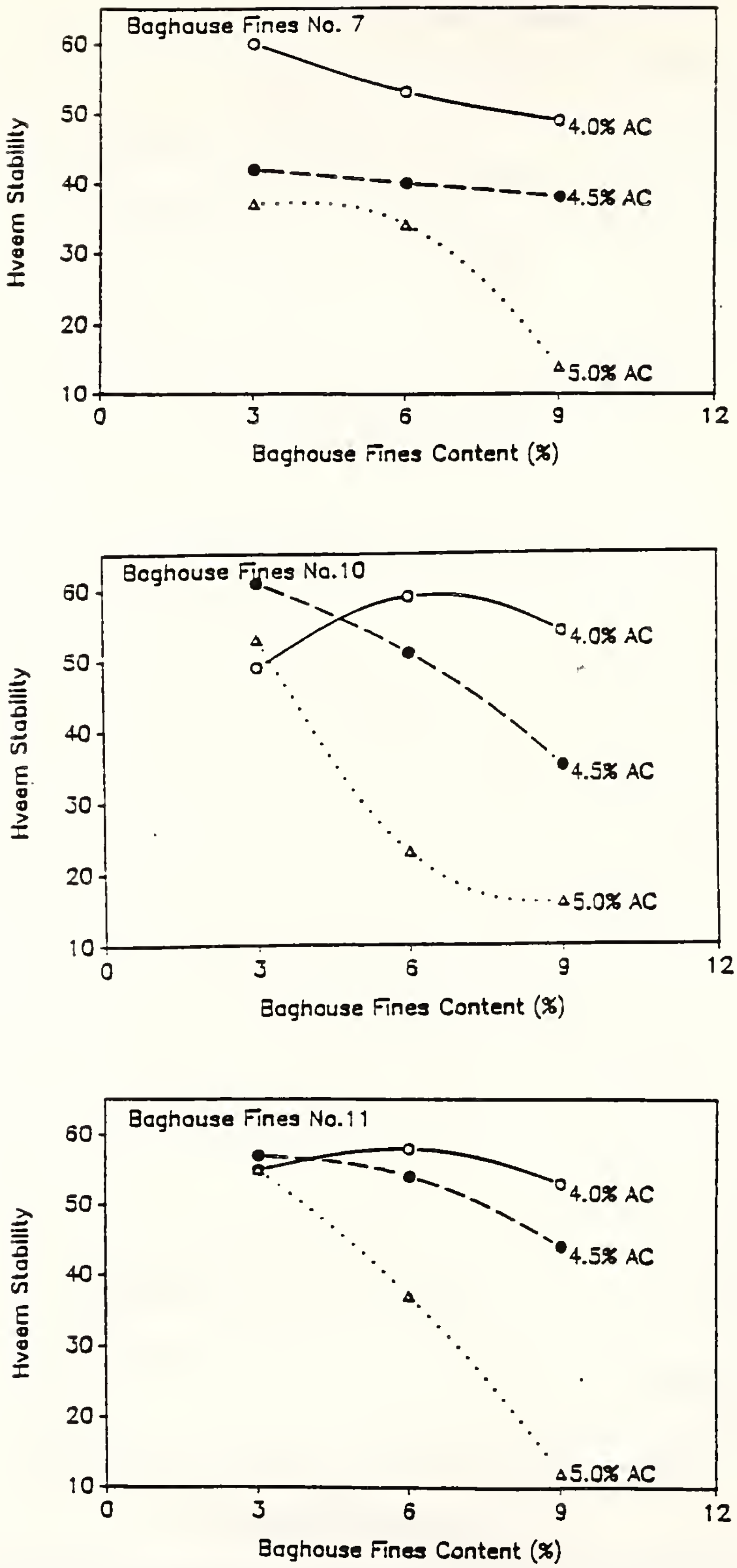


Figure 7.4 Hveem Stability of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 2)

(P), asphalt cement content (A) and their interactions PA, BP, BPA were significant in indirect tensile strength. The effect of baghouse fines was not significant.

Figure 7.4 presents the Hveem stability. The ANOVA results (Table 7.4) indicate that types of baghouse fines (B), percent of baghouse fines (P), percent of asphalt content (A) were significant.

Figure 7.3 and Figure 7.4 depicting the indirect tensile strength and Hveem stability are similar to Figure 7.2, in that the higher the baghouse fines content, the lower will be the strength of asphalt paving mixtures.

7.5 Summary of Results

The findings presented in this chapter, on the behavior of asphalt paving mixtures containing with baghouse fines, are summarized as follows:

1. The gyratory elasto-plastic index increased with increasing baghouse fines content when the asphalt content was above the optimum level.
2. The gyratory compactibility index was insensitive to change in baghouse fines content, type of baghouse fines and asphalt cement content.
3. The gyratory stability index was relatively insensitive for the lower baghouse fines content (3%) or low asphalt cement content (4.0%) but increased significantly as the baghouse fines content was greater than 6% and the

asphalt content was above 4.5%.

4. The gyratory stability index was very sensitive to the baghouse fines content in this test. The role of baghouse fines as an extender can be demonstrated by the gyratory testing machine. If one assumed a gyratory stability index equal to 1.20, the optimum asphalt content decreased about 0.5% to 1.0% as the baghouse fines content increased from 3% to 9%.
5. The resilient modulus decreased significantly with higher baghouse fines contents at normal and high temperatures. At the lower temperature this phenomenon is not significant. The decrease in resilient modulus with the baghouse fines content was caused by the extender action of asphalt cement and baghouse fines interaction. At lower baghouse fines content, the resilient modulus increased with asphalt cement content near or below the optimum level, and decreased as the asphalt cement content was above the optimum level.
6. The indirect tensile strength and Hveem stability versus asphalt cement content trends for different baghouse fines contents were similar to the resilient modulus trends for baghouse fines content. The baghouse fines which act as extenders decrease the indirect tensile strength and Hveem stability at higher baghouse fines contents.

CHAPTER 8

CONDITIONING OF ASPHALT PAVING MIXTURES WITH BAGHOUSE FINES

8.1 Introduction

Conditioning of asphalt paving specimens in the laboratory for the evaluation and design of mixtures includes both time and traffic effects. This chapter discusses those changes of asphalt paving mixtures due to time and traffic. Mixture conditioning includes the simulation of plant aging and environmental aging, moisture damage, and traffic densification.

One of the important factors in predicting the properties of asphalt paving mixtures and how these properties vary with time is the behavior of the asphalt cement with regard to aging hardening. The procedure generated in the NCHRP AAMAS projects (30) is to age the loose mix in a forced draft oven at 275°F for a period of 4 hours to simulate the production hardening in an asphalt plant. Environmental or inservice aging used the forced draft oven set at a temperature of 140°F for 2 days. After initial heating, the oven temperature is increased to 225°F for an additional 5 days.

Moisture conditioning is also an important factor to be evaluated for asphalt paving mixtures. Stripping or moisture damage is one of the detrimental characteristics of mixtures. Currently ASTM D4867 is the standardized procedure that has been developed to evaluate moisture damage of asphalt paving mixtures (29).

Traffic densification of asphalt paving mixtures is defined simply as an additional reduction in air voids after initial compaction. The gyratory testing machine can be used to evaluate how the properties of the mixture will vary with traffic loads and tire pressures.

This chapter presents the results of the three sets of experiments (Designs 3, 4, & 5) which dealt with the conditioning behavior of the asphalt paving mixtures. In design No. 3 (shown in Table 5.3), the asphalt paving mixtures tested were made from an artificially aged condition. In design No. 4 (shown in Table 5.4), the asphalt paving mixtures tested were made from a water saturation condition. In design No. 5 (shown in Table 5.5), the asphalt paving mixtures tested were made from a gyratory densification condition.

The main objectives of those experiments were as follows:

1. The characteristics of asphalt paving mixtures under different compactive efforts were evaluated using gyratory testing machine.
2. The effects of substituting baghouse fines for asphalt cement in asphalt paving mixture, while maintaining a constant volume of baghouse fines plus asphalt cement, were studied by performing indirect tensile and resilient modulus tests.
3. The effects of various methods of conditioning such as aging behavior, water damage, and densification upon the performance of asphalt paving mixtures were considered.
4. A statistical analysis was conducted to establish the significance and relationships among test parameters.

The general laboratory procedure described in chapter 4 was used to prepare and to test the asphalt paving mixtures. All loose mixes were subjected to initial aging which simulated the production in an asphalt plant. The aging was achieved in a forced draft oven at 275°F for 4 hours. The specimens were then fabricated by gyratory testing machine.

8.2 Aging Behavior

Compacted specimens of the asphalt paving mixtures containing different kinds and contents of baghouse fines were artificially aged by storage in a forced draft oven set at a temperature of 140°F for 2 days and then elevated to 225°F for 5 days. The independent variables included the kinds of baghouse fines, the baghouse fines/asphalt cement ratio added, (maintaining a constant volume of baghouse fines and asphalt cement), the aging time, and the testing temperature. Gyratory parameters were obtained during the compaction process. The properties of the asphalt paving mixtures measured at various temperatures were the resilient modulus, the indirect tensile strength, and failure tensile strain. The above response variables were obtained at the same temperature and compared with the same parameters obtained for non aged specimens.

8.2.1 Gyratory Parameters

The gyratory parameters for asphalt paving mixtures containing baghouse fines were collected during the compaction process.

ANOVAs were performed on the obtained data using the following model:

$$Y_{ijkl} = \mu + F_i + \delta_{(i)} + B_j + P_k + PB_{jk} + G_l + FB_{ij} + FP_{jk} + FG_{il} + PG_{jl} + \ldots\ldots + \epsilon_{ijklm} \text{------------------------------} 8.1$$

Where Y_{ijklm} = Response variable: GEPI, GSI, GCI, and r_d

μ = Overall mean of response variable

F_i = Effect of different time of fabricating specimens

B_j = Effect of different kinds of baghouse fines

P_k = Effect of percent of baghouse fines and asphalt cement content added

G_l = Effect of aging

δ_i = Restriction error

ϵ = Experimental error

FB_{ij} FP_{ik} $FG_{il} \ldots\ldots FBPG_{ijkl}$ = Effects of intersections of factors

$i,l = 1,2$ $j,k = 1,2,3$ $n = 1,2$

This is a randomized factorial design. The ANOVA results are presented in Table 8.1. It can be noted that the gyratory compactibility index, gyratory elasto-plastic index, and unit weight of specimens were insensitive to the changes of baghouse fines/asphalt cement ratio, different kinds of baghouse fines, aging time, and fabricating time. Figure 8.1 indicates that the gyratory stability index (GSI) increased with an increasing asphalt content (decreasing baghouse fine/asphalt cement ratio) and then decreased as the asphalt cement content increased above the optimum

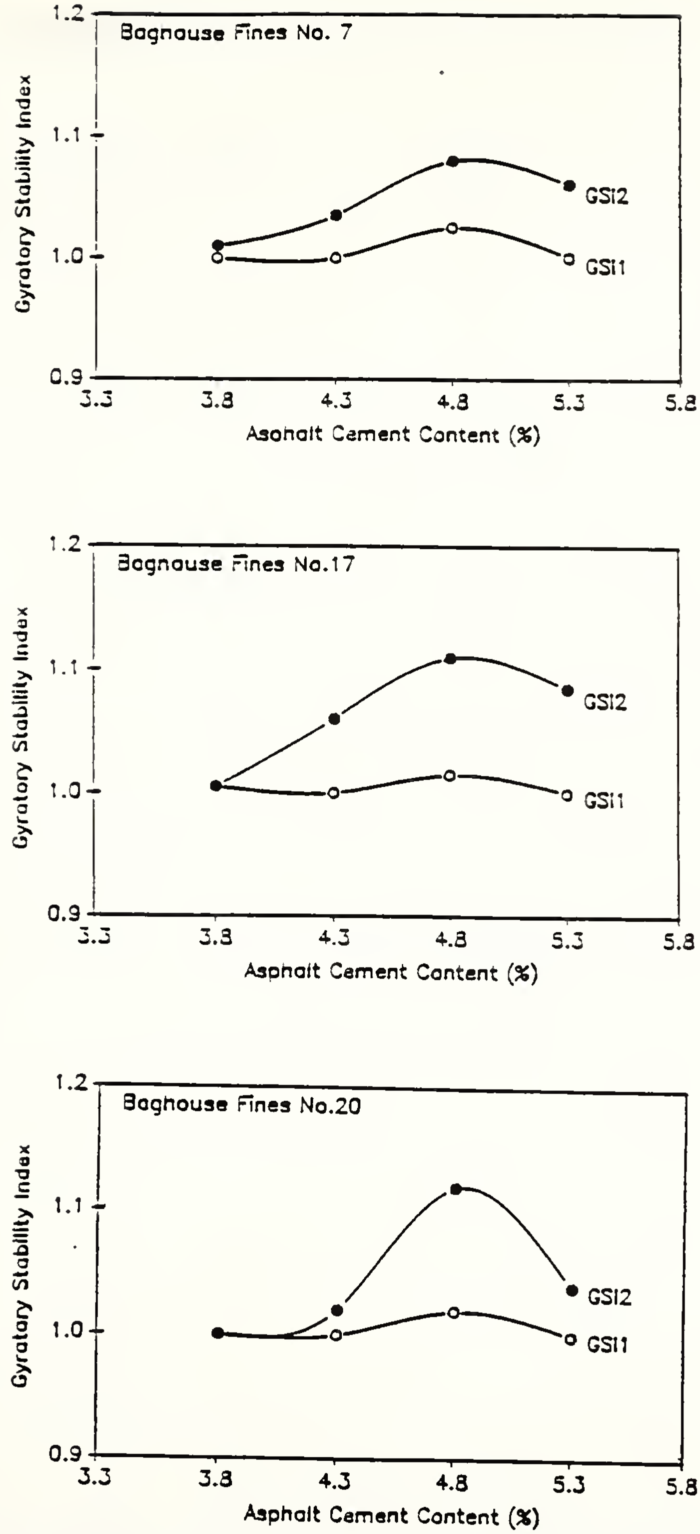


Figure 8.1 Gyratory Indices of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3)

Table 8.1 ANOVA Results for Gyratory Parameters (Design No. 3)

Source of Variation	GEPI	Response GSI1	Variables GSI2	GCI	r_d
F	N.S.	N.S.	N.S.	N.S.	N.S.
B	N.S.	N.S.	N.S.	N.S.	N.S.
P	N.S.	S.	S.	N.S.	N.S.
G	N.S.	S.	S.*	N.S.	N.S.
FB	N.S.	S.*	N.S.	N.S.	N.S.
FP	N.S.	S.	N.S.	N.S.	N.S.
FG	N.S.	N.S.	S.	N.S.	N.S.
BP	N.S.	N.S.	N.S.	S.*	N.S.
BG	N.S.	N.S.	N.S.	N.S.	N.S.
PG	N.S.	N.S.	S.	N.S.	N.S.

S. = significant at α = 0.05, N.S. = not significant at α = 0.05

S.* = significant at α = 0.10

level for both compactive efforts (GSI1=30 revolutions, GSI2=60 revolutions)

Results of the gyratory parameters are tabulated in Appendix C-1. Test results include data on each replicate tested as well as the average of the two replicates tested.

8.2.2 Resilient Modulus

The resilient moduli of asphalt paving mixtures containing baghouse fines in Design 3 are presented in Figure 8.2 and 8.3, as a function of asphalt cement content (baghouse fines/asphalt cement ratio), aging, and temperature. It can be observed that the resilient modulus decreased as asphalt content increased (baghouse fines/asphalt cement ratio decreased), but at a higher asphalt cement content, the change of the resilient modulus was minimal. Drastic increases in the resilient modulus were caused by the artificial aging process. The resilient modulus increased by 400% to 1000% due to artificial aging for mixtures with different kinds of baghouse fines especially at lower asphalt cement content (higher baghouse fines/asphalt cement ratio) and the higher testing temperature (40°C). The resilient modulus only increased about 80% to 200% at higher asphalt cement contents (lower baghouse fines/asphalt cement ratio) at lower testing temperatures. This could imply that the aging process may be more detrimental for lower asphalt cement content (higher baghouse fines/asphalt cement ratio) and at higher pavement temperatures.

ANOVA were performed on the resilient modulus data using the following statistical model:

$$Y_{ijklm} = \mu + B_i + P_j + BP_{ij} + S(BP)_{(ij)k} + \delta_{ijk} + O_l + BO_{il} + PO_{jl} + OBP_{ijl} + S(BP)O_{(ij)kl} + w_{ijkl} + T_m + BT_{im} + PT_{jm} + OT_{lm} + \ldots \epsilon_{ijklm} \qquad \text{8.2}$$

The model is similar to the general model described in the previous Chapter 7, with the exception that the compactive effort terms were replaced by oven effect. The results of ANOVA are presented in Table 8.2.

The ANOVA results indicate that the effects of asphalt cement content (baghouse fines/asphalt cement ratio, P), aging time (O), and testing temperature (T) were all significant at $\alpha = 0.05$. The interaction terms PO, BT, PT, TO were also significant.

Figure 8.2 presents the resilient modulus for various aging conditions at a different testing temperatures. It can be noted that the ratio of the resilient modulus for any condition divided by the resilient modulus for non-aging (aging index) increased as the testing temperature increased. Figure 8.3 presents the resilient modulus of asphalt paving mixtures near optimum asphalt content at different stages of aging.

The test results of resilient modulus are tabulated in Appendix C-2. Test results include data on each replicate test.

8.2.3 Hveem Stability

The test results of Hveem stability as tabulated in Appendix C-3 were analyzed as a result of the factorial experiment

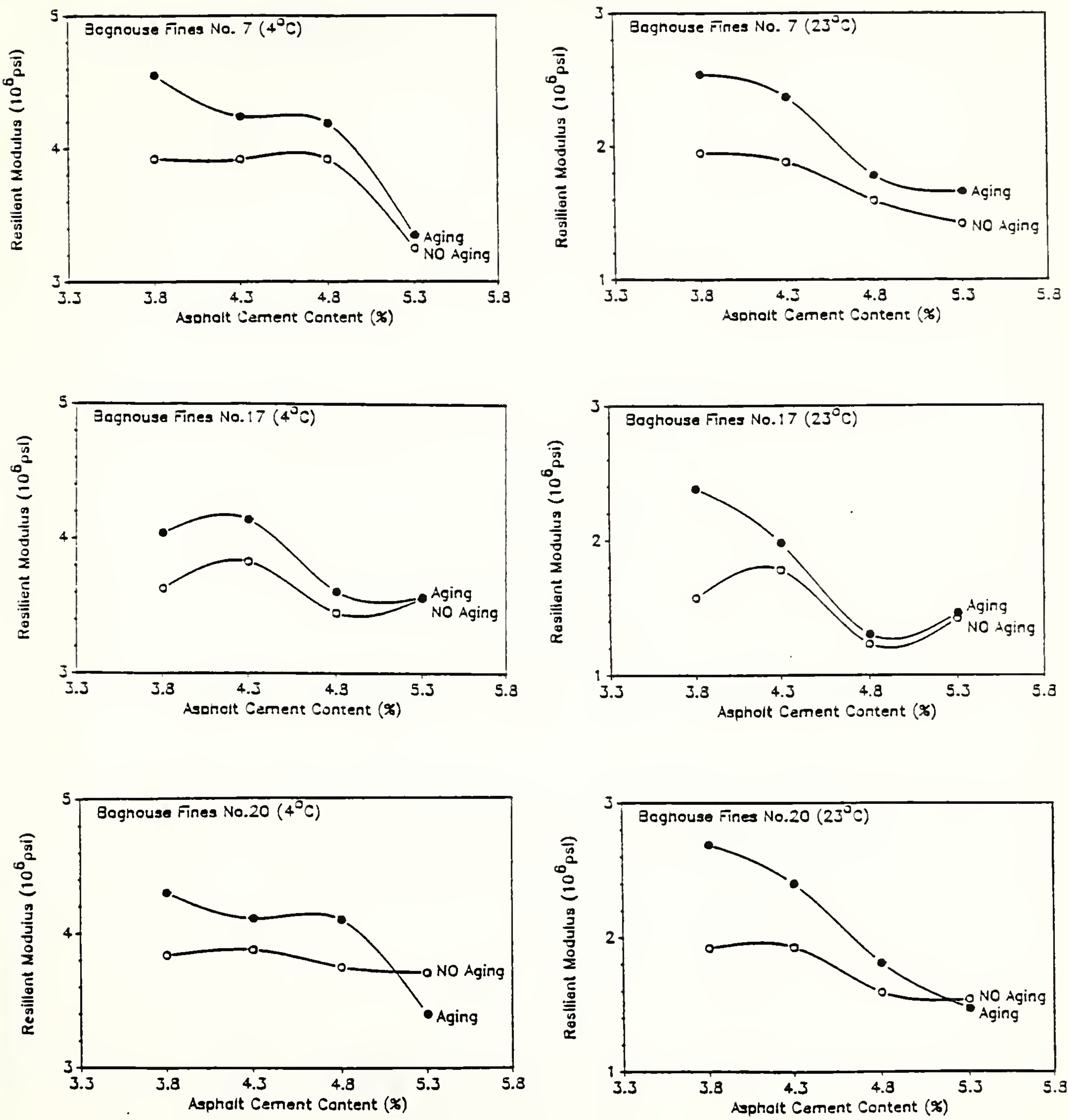


Figure 8.2 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3) (Continue)

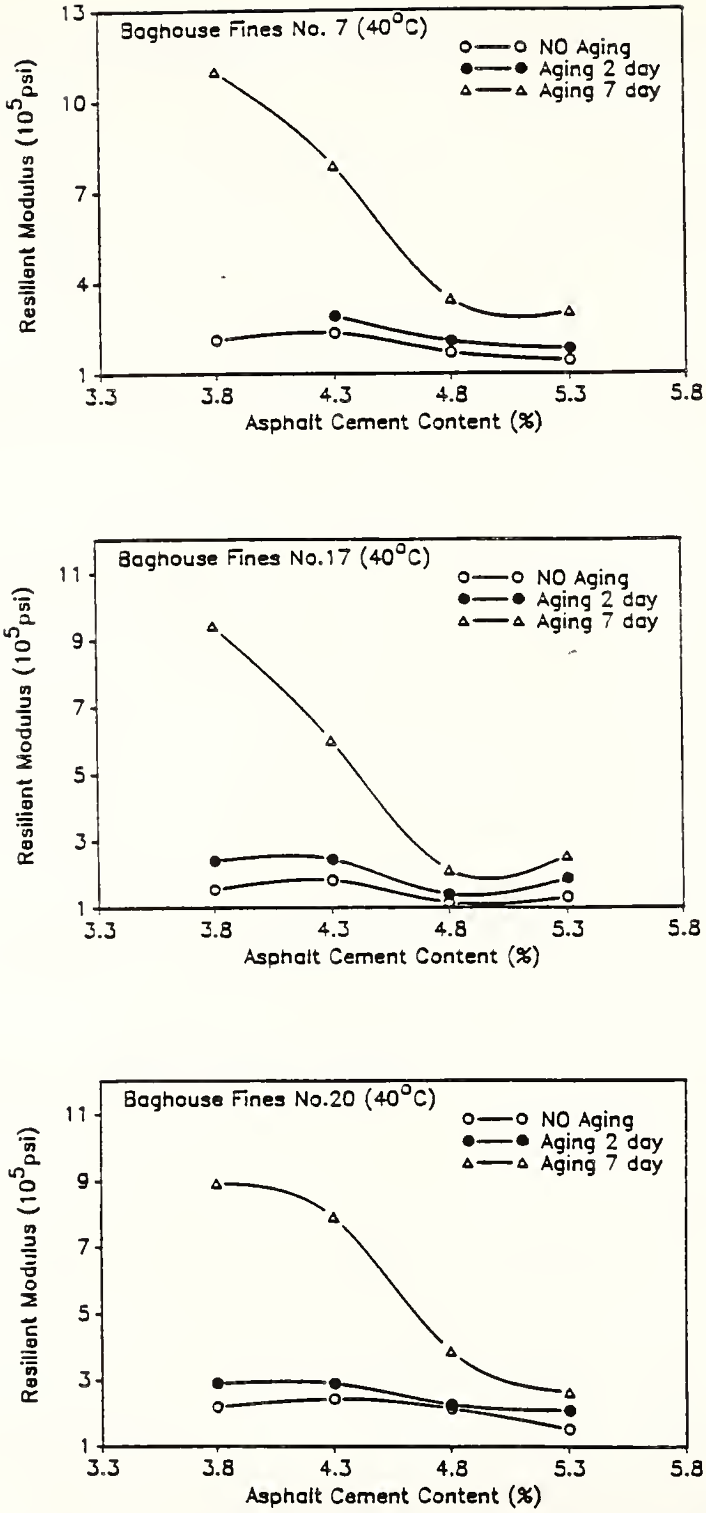


Figure 8.2 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3)

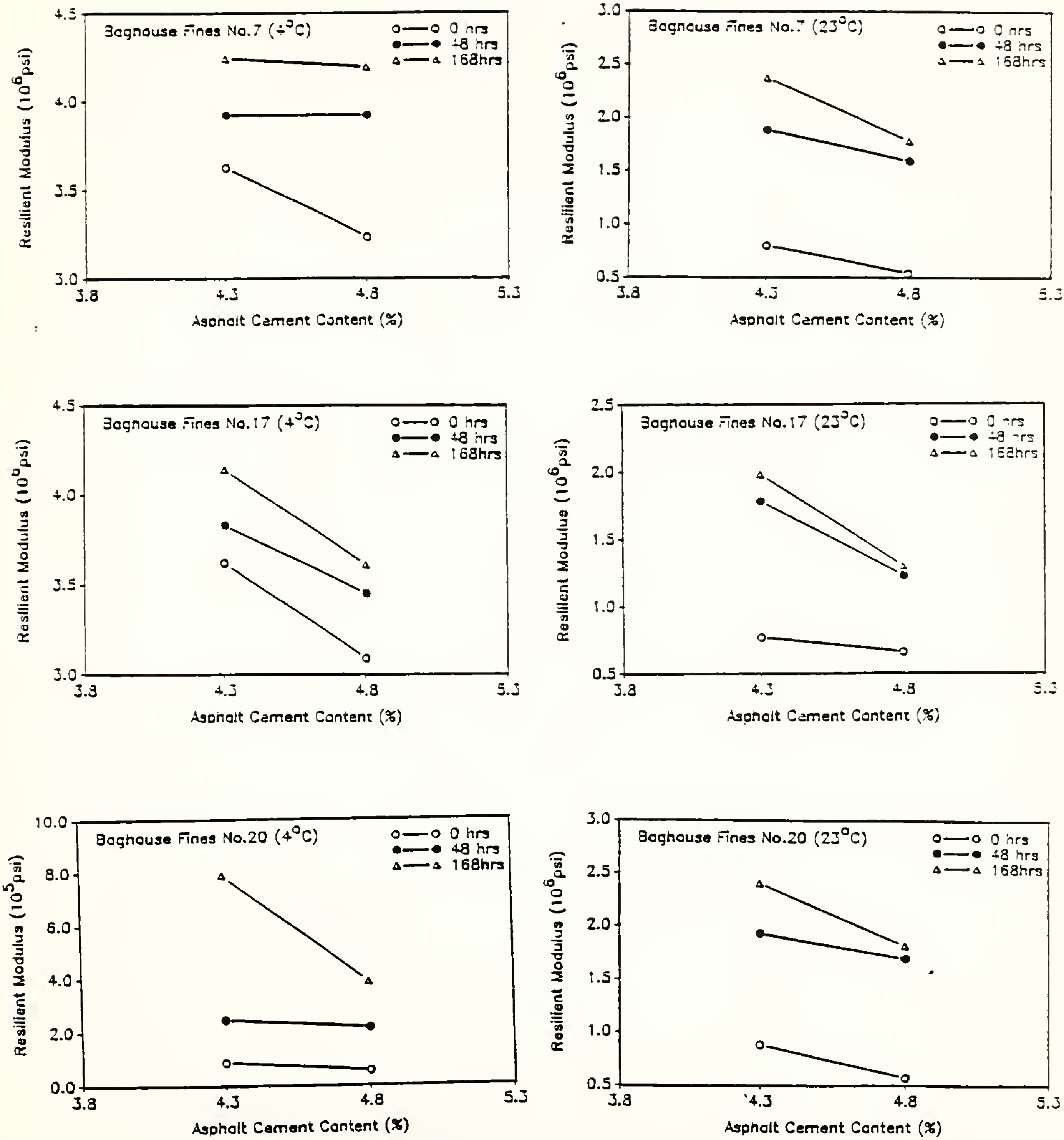


Figure 8.3 Resilient Modulus of Asphalt Paving Mixtures with Optimum Asphalt Cement Content at Different Aging Conditions (Design No. 3) (Continue)

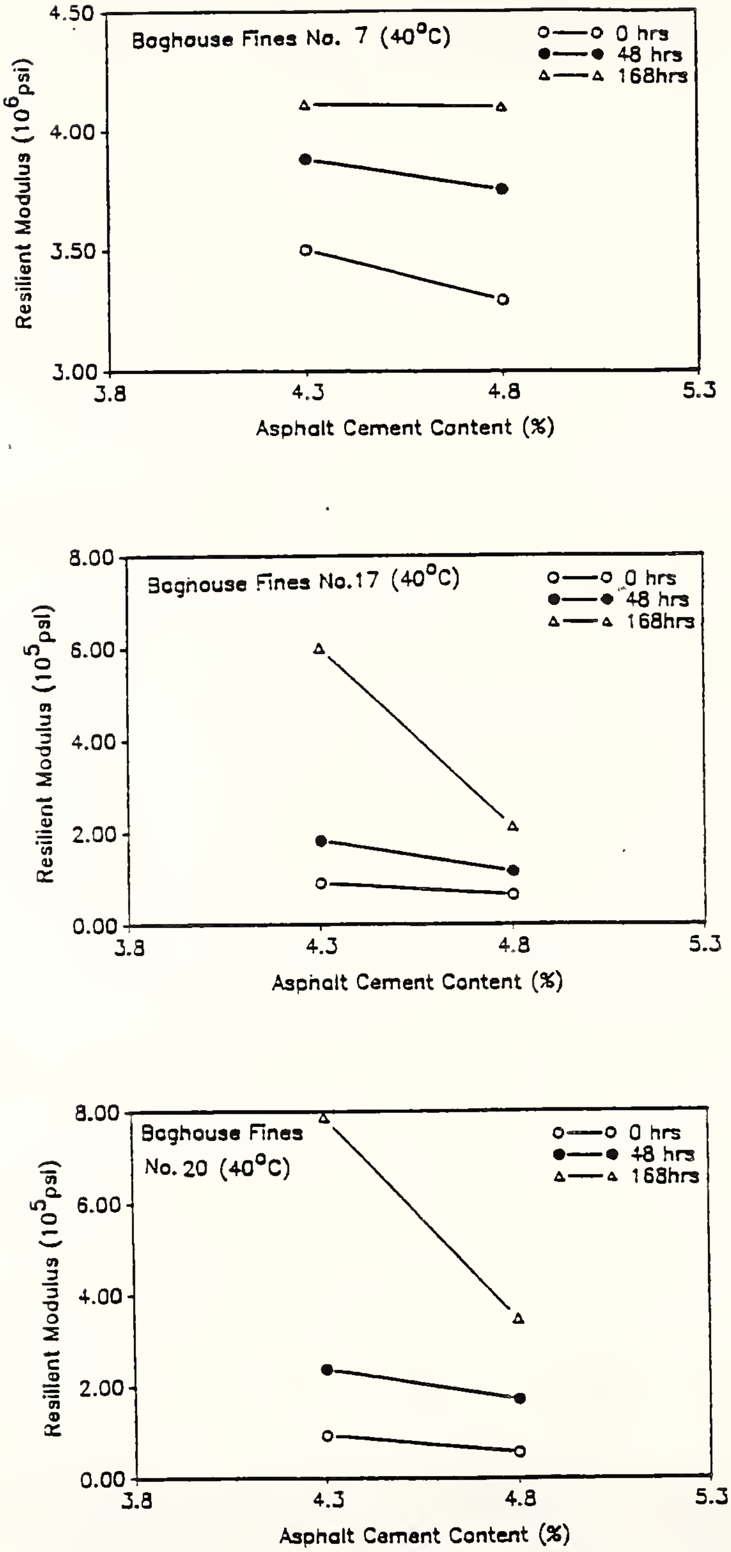


Figure 8.3 Resilient Modulus of Asphalt Paving Mixtures with Optimum Asphalt Cement Content at Different Aging Conditions (Design No. 3)

Table 8.2 ANOVA Results for Resilient Modulus (Design No. 3)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	2	89.8	44.9	2.43	0.130
P	3	289.6	96.5	5.22	0.0155
BP	6	33.4	5.6	0.30	0.9247
S(BP)	12	222.0	18.5		
O	2	160.4	80.2	22.05	0.0001
BO	4	10.4	2.6	0.71	0.5905
PO	6	97.4	16.3	4.46	0.0036
BPO	12	21.4	1.8	0.49	0.9006
S(BP)O	24	87.3	3.6		
T	1	9926.1	9926.1	4614.60	0.0001
BT	2	39.4	19.7	9.18	0.0011
PT	3	43.1	14.4	6.67	0.0020
BPT	6	31.2	5.2	2.42	0.0570
S(BP)T	12	81.8	6.8	3.17	0.0078
OT	2	10.6	5.3	2.47	0.1055
BOT	4	9.9	2.5	1.15	0.3563
POT	6	27.1	4.5	2.10	0.0907
BPOT	12	13.3	1.1	0.51	0.8856
S(BP)OT	24	51.6	2.2		
ϵ	131	231.06			
	274	14899.33			

comprising three kinds of baghouse fines, asphalt cement content (baghouse fines/asphalt cement ratio), and aging time. ANOVAs were performed on obtained data using the following model:

$$Y_{ijkl} = \mu + B_i + P_j + BP_{ij} + O_k + BO_{ik} + PO_{jk} + BPO_{ijk} + \epsilon_{ijkl} \text{--8.3}$$

The terms in the model are as defined earlier. The ANOVA results are presented in Table 8.3. Figure 8.4 depicts the relationship between Hveem stability and baghouse fines/asphalt cement ratio under aging condition. Results from Hveem stability show that there are significant differences among asphalt cement contents, (baghouse fines/asphalt cement ratio), and aging condition. The Hveem stability decreased for the aged condition at asphalt cement contents less than the optimum and increased for values greater than the optimum. The unaged condition displayed only minor changes in Hveem stability at increasing asphalt cement content.

8.2.4 Indirect Tensile Strength

Indirect tensile strength and failure tensile strain measurements were collected on asphalt paving mixtures containing different asphalt cement contents (baghouse fines/asphalt cement ratio). ANOVAs were performed on the obtained data using the same statistical model as for the Hveem stability, with the addition of the testing temperature terms and their interaction terms. The ANOVA results are represented in Table 8.4 and Table 8.5. Figure

Table 8.3 ANOVA Results of Hveem Stability
(Design No. 3)

Source of Variation	df	SS	MS	F	PR>F
B	2	174.93	87.47	4.76	0.0577
P	3	476.72	155.91	8.49	0.0140
O	1	126.04	126.04	6.87	0.0396
BP	6	42.18	7.03	0.38	0.8661
BO	2	79.31	39.66	2.16	0.1965
PO	3	168.13	56.04	3.05	0.1136
ϵ	6	110.13	18.36		
	23	1168.43			

Table 8.4 ANOVA Results of Indirect Tensile Strength
(Design No. 3)

Source of Variation	df	SS	MS	F	PR>F
B	2	318.38	159.19	0.19	0.8294
P	3	28631.23	954.37	11.31	0.0001
O	1	2451.02	2451.02	2.90	0.1018
T	1	1425196.69	1425196.69	1688.54	0.0001
BP	6	3988.96	664.83	0.79	0.5886
BT	2	4331.38	2165.69	2.57	0.1002
BO	2	4299.29	2149.6	2.55	0.0987
PO	3	1922.23	640.74	0.76	0.5285
PT	3	16441.23	5480.41	6.49	0.0024
OT	1	475.02	475.02	0.56	0.4607
ϵ	23	19412.90			
	47	1507468.31			

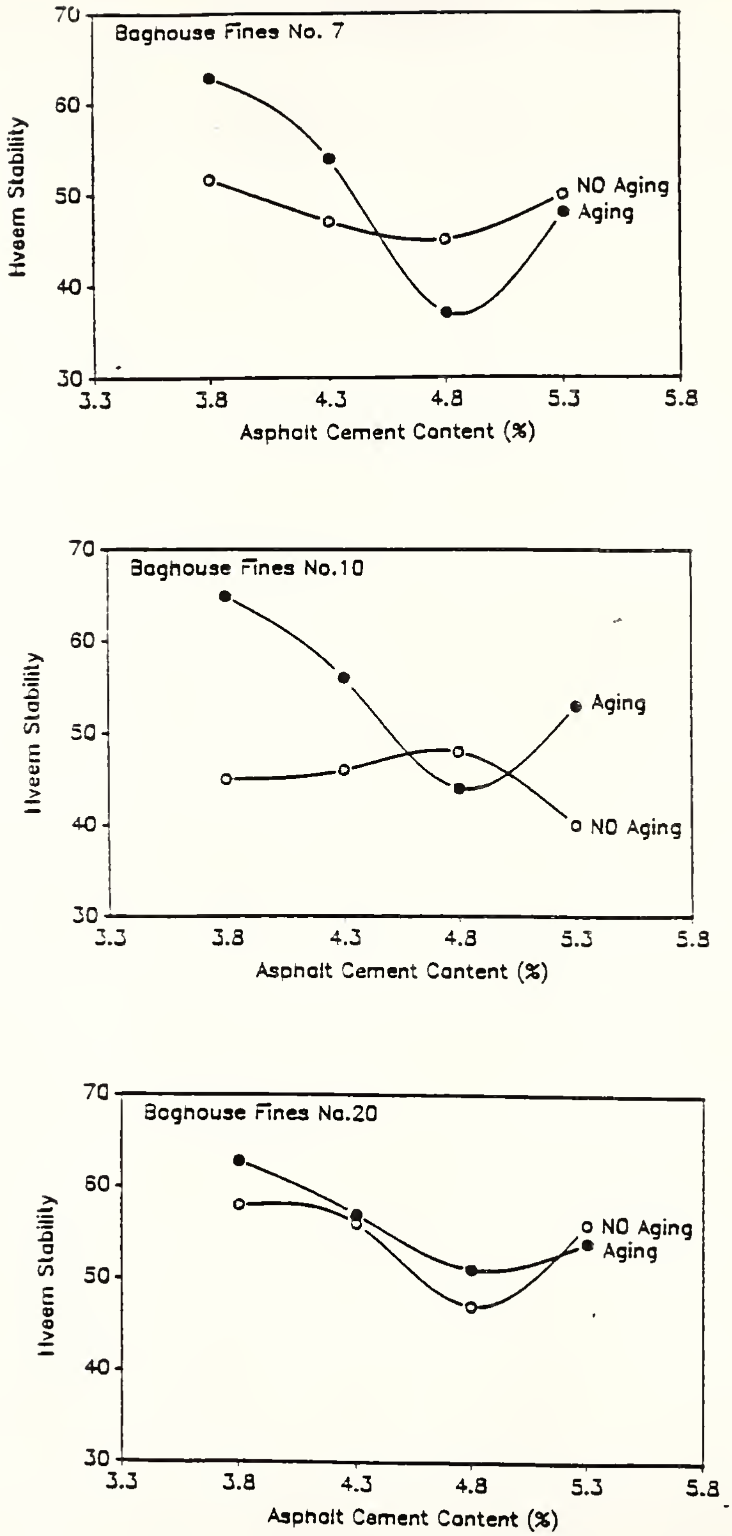


Figure 8.4 Hveem Stability of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3)

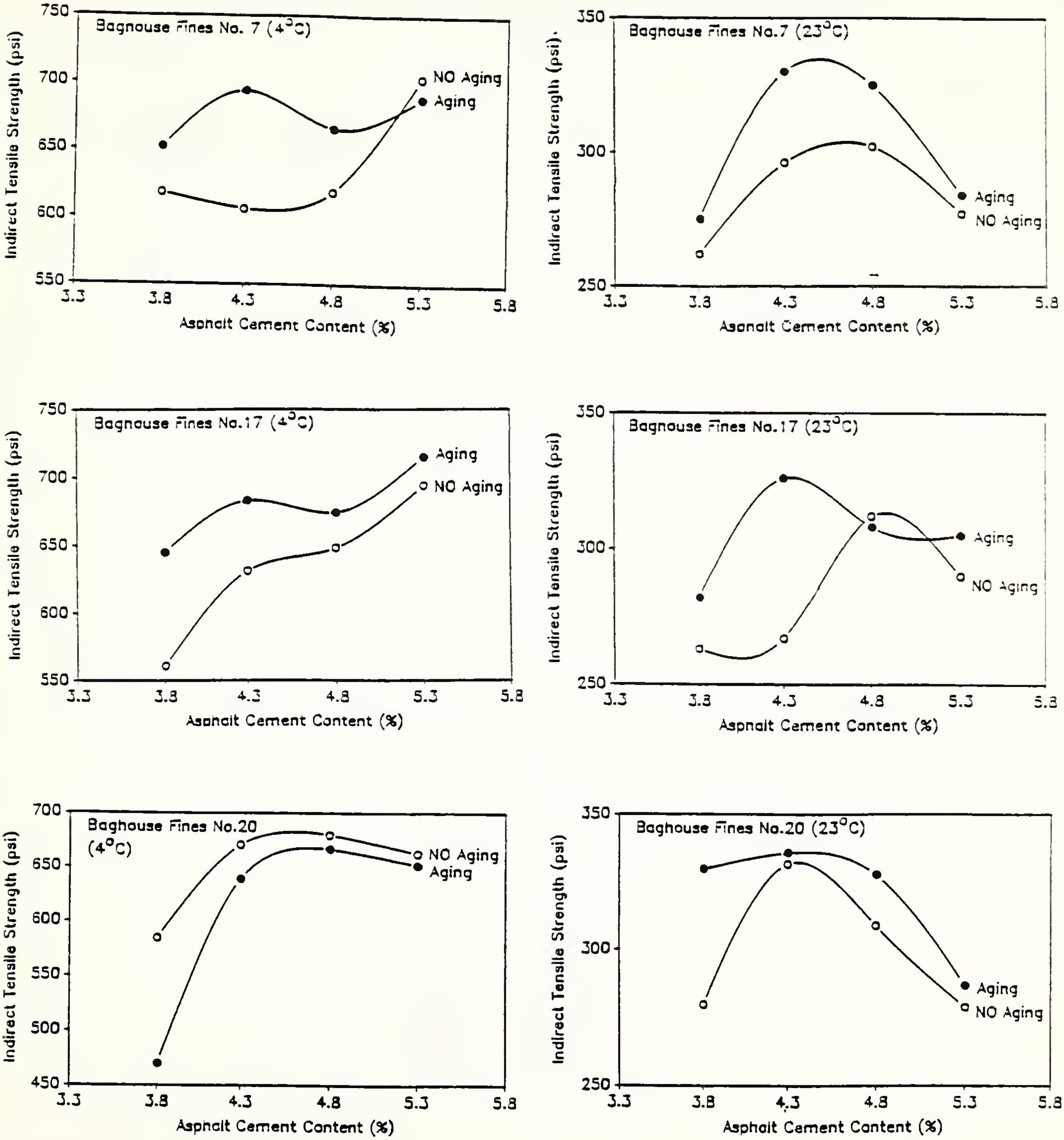


Figure 3.5 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3)

Table 8.5 ANOVA Results of Failure Tensile Strain (Design No. 3)

Source of Variation	df	SS	MS	F	PR>F
B	2	0.166	0.083	0.69	0.5117
P	3	1.116	0.372	3.09	0.0472
O	1	4.083	4.083	33.89	0.0001
T	1	18.500	18.500	153.57	0.0001
BP	6	1.180	0.197	1.63	0.1832
BO	2	0.125	0.063	0.52	0.6010
BT	2	0.550	0.275	2.28	0.1245
PO	3	0.137	0.046	0.38	0.7696
PT	3	0.329	0.109	0.91	0.4511
OT	1	0.213	0.213	1.77	0.1963
ϵ	23	2.771	0.121		
	47	29.173			

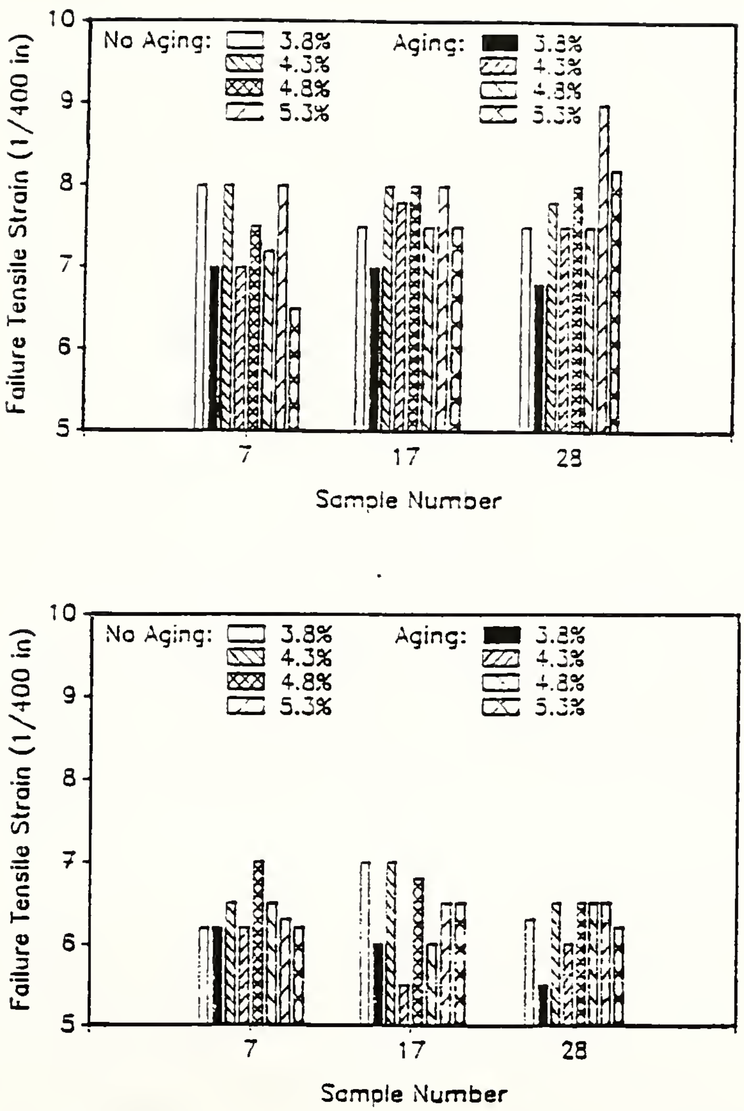


Figure 8.6 Failure Tensile Strain of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 3)

8.5 depicts the indirect tensile strength under different aging conditions. The indirect tensile strength for asphalt paving mixtures increased by different percentages due to the aging process for mixtures that contained different baghouse fines and asphalt cement contents (baghouse fines/asphalt cement ratio) at room temperature. However no such trend was observed at the low temperature.

Failure tensile strain decreased for all paving mixtures due to aging. Artificial aging caused the failure tensile strain to be less at lower temperatures than at room temperature (Figure 8.6).

The effect of different baghouse fines on indirect tensile strength and failure tensile strain was not significant. However, asphalt cement content (the baghouse fines/asphalt cement ratio), aging condition, and testing temperature were significant. From Figure 8.5 it can be seen that at room temperature the indirect tensile strength was increased by aging asphalt paving mixtures, but at low temperature the indirect tensile strength was only increased by aging asphalt paving mixtures at higher baghouse fines/asphalt cement ratio (lower asphalt cement content).

8.2.5 Summary of Results

1. The gyratory elasto-plastic index and the gyratory compactibility index did not show any distinct trend for the changes of the asphalt cement content (baghouse fines/asphalt cement ratio). The gyratory stability index was sensitive to the changes in the level of asphalt cement content (baghouse

fines/asphalt cement ratio).

2. Artificial aging processes caused an increase in the indirect tensile strength and resilient modulus as well as reduction in the failure tensile strain values for asphalt paving mixtures. Asphalt paving mixtures containing a low asphalt cement content (high baghouse fines/asphalt cement ratio) tend to age more rapidly than a high asphalt cement content (low baghouse fines/asphalt cement ratio).
3. Resilient modulus and indirect tensile test parameters were more sensitive to the aging condition of asphalt paving mixtures than the Hveem stability. Both tests are potential methods for the study of the aging behavior of mixtures.
4. The level of asphalt cement content (baghouse fines/asphalt cement ratio) added to the asphalt had significant effect on the resilient modulus, indirect tensile strength, gyratory stability index.
5. The effects of different kinds of baghouse fines were not significant, when asphalt cement was replaced with baghouse fines in order to maintain a constant volume of asphalt cement plus baghouse fines.

8.3 Water Sensitivity

ASTM D4687 and AASHTO T283 are currently the standardized procedures that have been developed to evaluate moisture damage of asphalt paving mixture. Four test specimens for each set of mix conditions are tested. Each set of specimens is divided into two groups and tested in a dry condition (stage 1) for indirect tensile strength and resilient modulus. The other group is subjected to vacuum saturation (stage 2) followed by a freeze and warm water soaking cycle (stage 3) and then tested for resilient modulus and indirect tensile strength. The independent variables included the kinds of baghouse fines, baghouse fines/asphalt cement ratio added (maintaining a constant volume of asphalt cement and baghouse fines), the saturation condition, and the testing temperature. Gyratory parameters were obtained during the compaction process. The properties of the asphalt paving mixtures measured at various temperatures were the resilient modulus, the indirect tensile strength, and the failure tensile strain. Hveem stability is unacceptable for predicting moisture susceptibility of asphalt paving mixtures (33). The above response variables were obtained at the same circumstances and compared with the same parameters obtained for dry specimens.

8.3.1 Gyratory Parameters

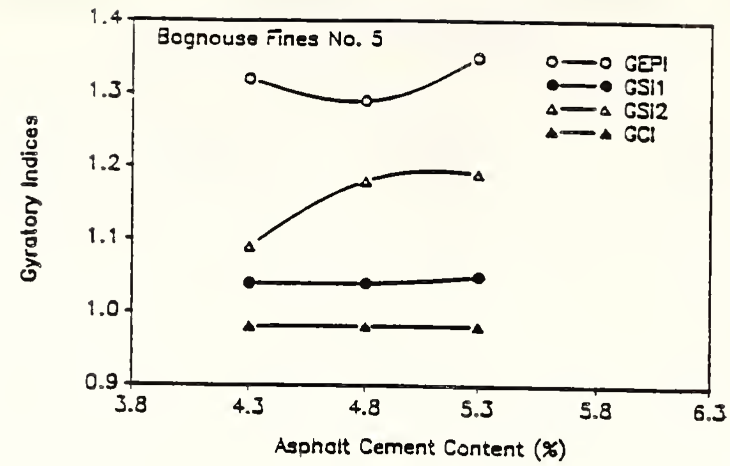
The gyratory parameters for asphalt paving mixtures containing baghouse fines were read during the compaction process. ANOVAs were performed on obtained data using the statistical model which was the same as section 8.2 (page ???). The ANOVA results are presented in Table 8.6. It can be noted that the gyratory compactibility index, gyratory elasto-plastic index, and unit weight of specimens were insensitive to the changes of asphalt cement content (baghouse fines/asphalt cement ratio), aging time

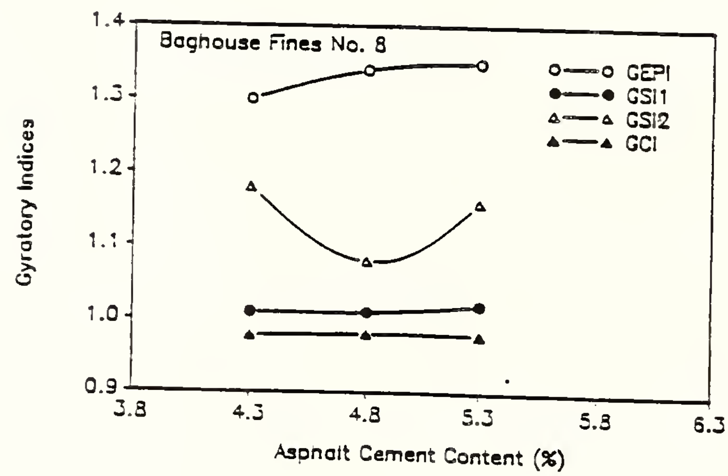
Table 8.6 ANOVA Results for Gyratory Parameters (Design No. 4)

Source of Variation	GEPI	Response GSI1	Variables GSI2	GCI	rd
F	N.S.	S.	S.	N.S.	S.*
B	N.S.	S.	S.*	S.	N.S.
P	N.S.	S.	S.	N.S.	N.S.
G	N.S.	N.S.	S.	N.S.	N.S.
FB	N.S.	N.S.	N.S.	N.S.	N.S.
FP	N.S.	N.S.	S.*	N.S.	N.S.
FG	N.S.	N.S.	S.*	N.S.	N.S.
BP	N.S.	N.S.	N.S.	N.S.	N.S.
BG	N.S.	N.S.	N.S.	N.S.	N.S.
PG	N.S.	N.S.	N.S.	N.S.	N.S.

S. = significant at $\alpha = 0.05$, N.S. = not significant at $\alpha = 0.05$,

S.* = significant at $\alpha = 0.10$





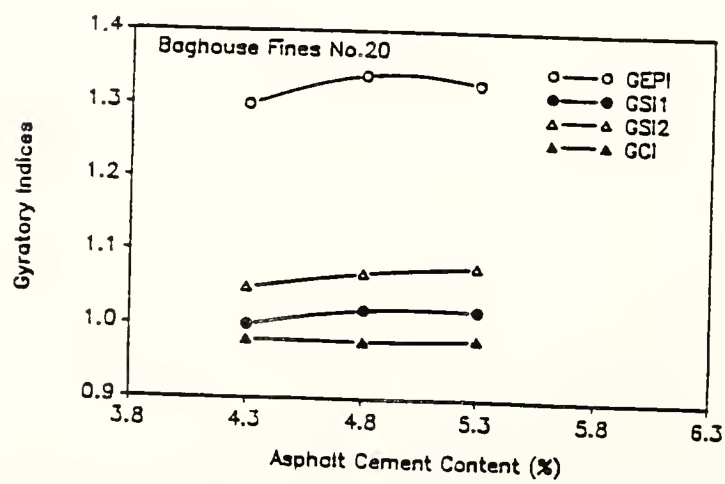


Figure 8.7 Gyratory Indices of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 4)

and fabricating time. Figure 8.7 shows that the gyratory stability index (GSI) increased with increased asphalt cement content (decreasing baghouse fines/asphalt cement ratio). Results of gyratory parameters are tabulated in Appendix C-5. The gyratory compactibility index of baghouse fines No. 5 was higher than No. 8 and No. 20. This was probably due to the fine state of subdivision of baghouse fines No. 5.

8.3.2 Resilient Modulus

The resilient modulus of asphalt paving mixtures containing baghouse fines as outlined in Design 4 are presented in Figure 8.8 and Figure 8.9 as a function of asphalt cement content (baghouse fines/asphalt cement ratio), water saturation, and temperature. It can be observed that the resilient modulus decreased as asphalt cement content increased (baghouse fines/asphalt cement content decreased) in dry condition. The moisture condition represented by saturation (stage 3) in Figure 8.8 created the situation such that the resilient modulus decreased as the asphalt cement content increased (baghouse fines/asphalt cement ratio decreased), reached a minimum and then increased with high asphalt content. The trend of resilient modulus increase may be caused by the pore pressure existing in the voids of the specimen at room temperature. The resilient modulus always decreased as asphalt cement increased (baghouse fines/asphalt cement ratio decreased) at higher temperatures (eg. 104°F). This could imply that water damage may be more severe for lower asphalt cement contents (higher baghouse

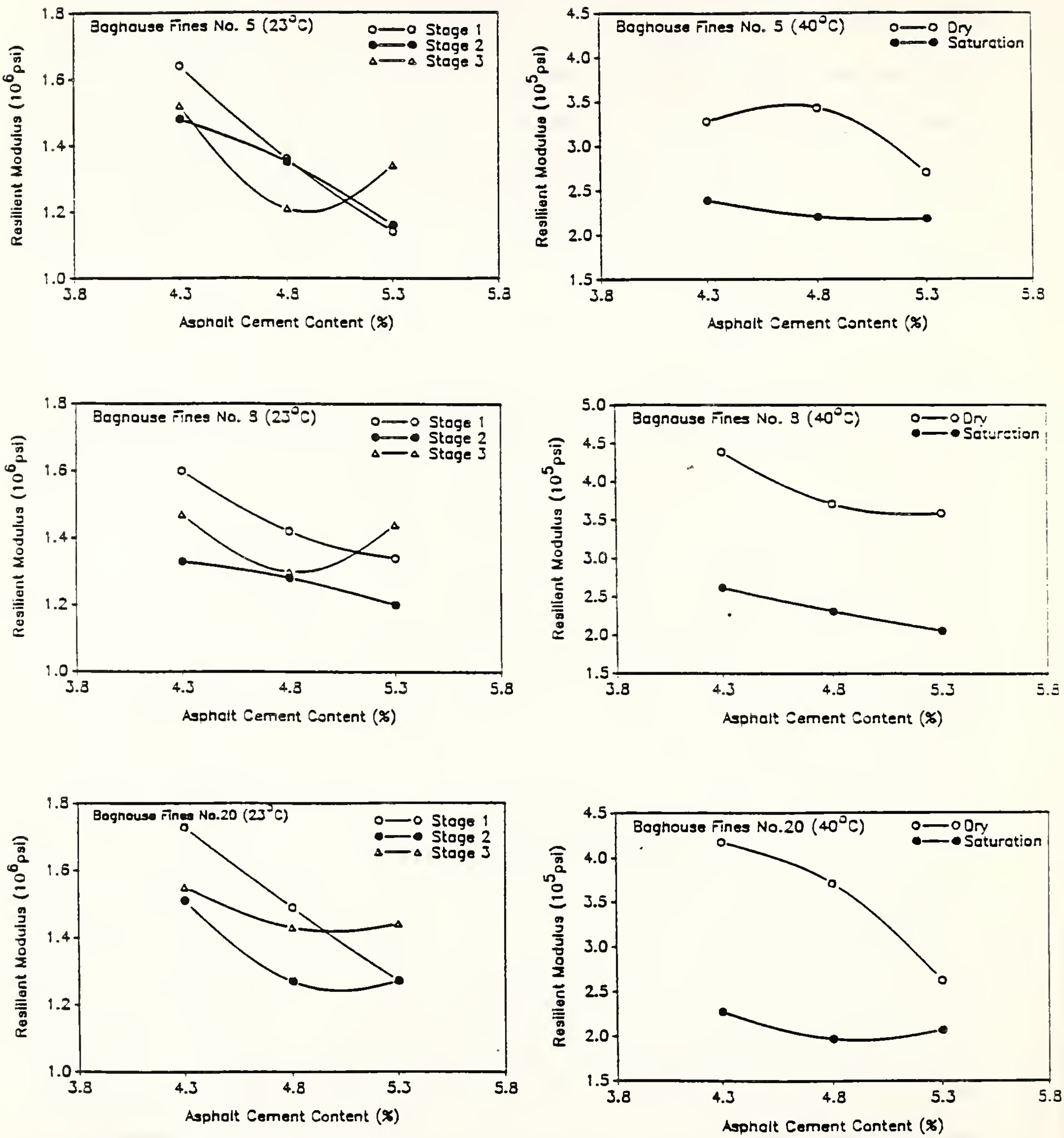


Figure 8.8 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 4)

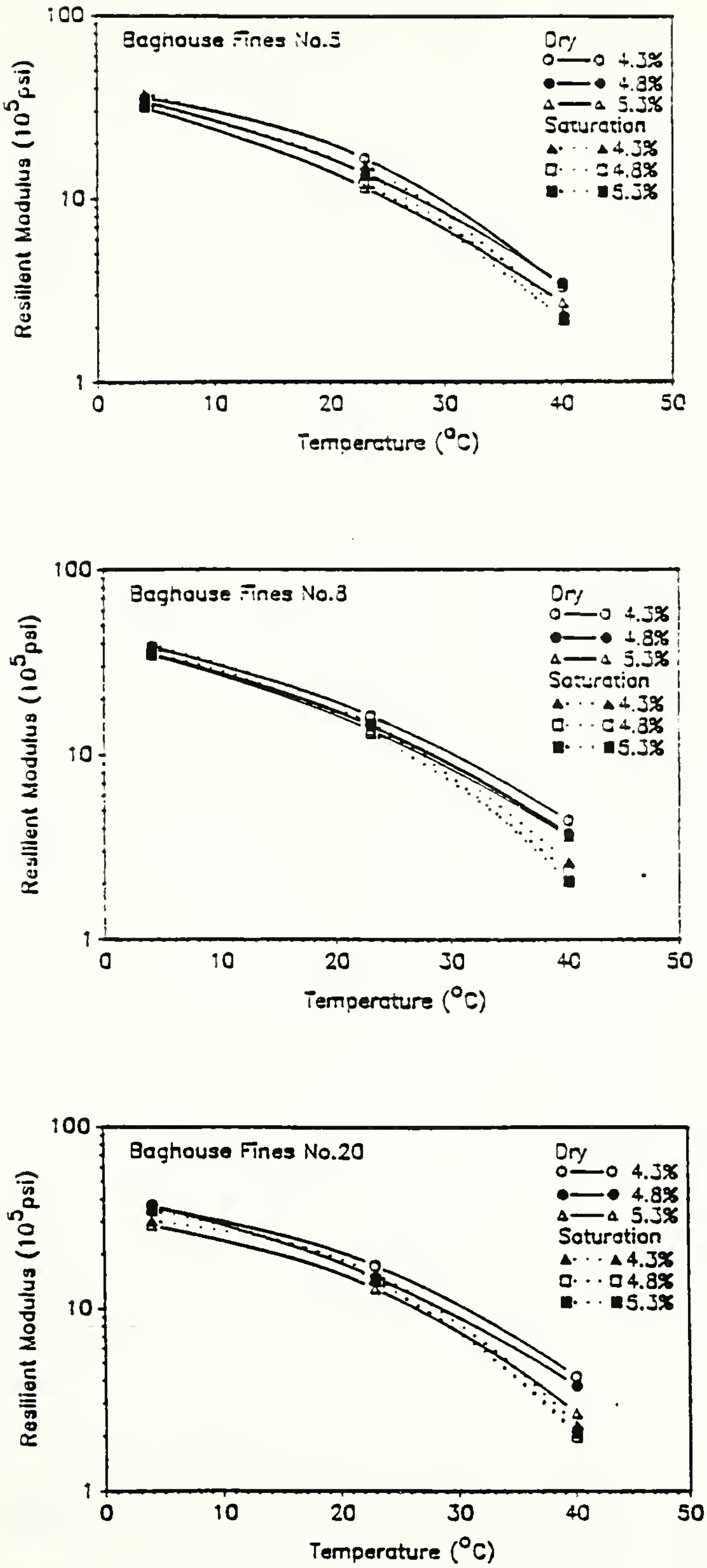


Figure 8.9 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content at Different Testing Temperature (Design No. 4)

fines/asphalt cement ratio) and at higher pavement temperatures.

ANOVA were performed on the results of resilient modulus test using the following statistical model:

$$Y_{ijklm} = \mu + B_i + P_j + BP_{ij} + S(BP)_{(ij)k} + \delta_{ijk} + W_l + BW_{il} + PW_{jl} + BPW_{ijl} + S(BP)W_{(ij)kl} + w_{ijkl} + T_m + BT_{im} + PT_{jm} + WT_{lm} + \ldots + \epsilon_{ijklm} \quad \text{------} \quad 8.4$$

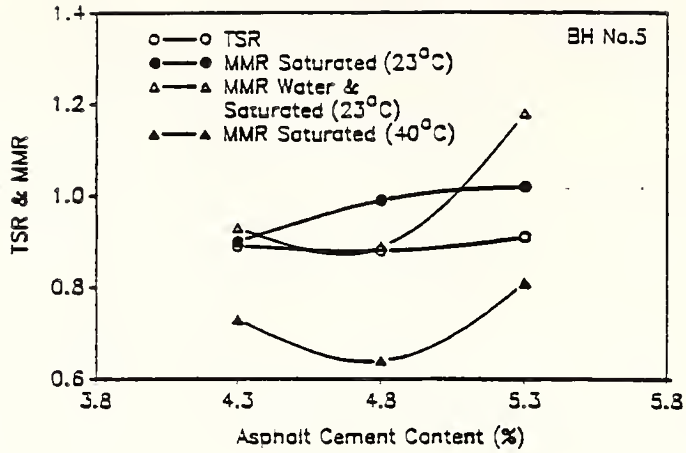
The model is similar to the formula 8.2 described in the previous section with the exception that the oven effect terms were replaced by water saturation. The results of ANOVA are present in Table 8.7.

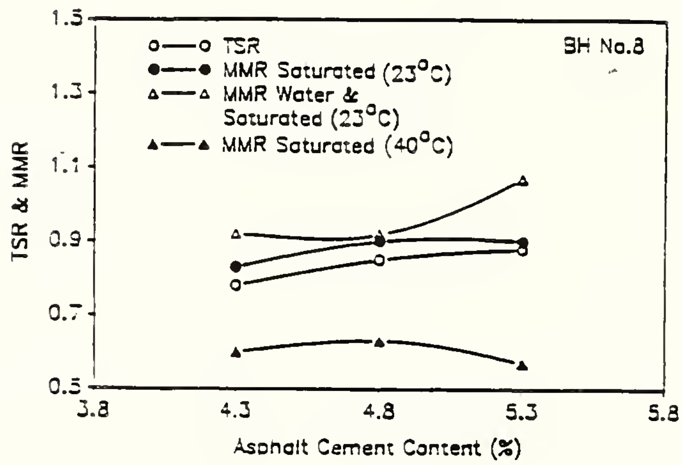
The ANOVA results indicate that the effects of asphalt cement content (baghouse fines/asphalt cement ratio, P), water saturation (W), and testing temperature (T) were all significant at $\alpha = 0.05$. The interaction terms BT, PW, PT, WT, and BWT were also significant. Figure 8.9 presents the effects of moisture condition and different testing temperatures upon the resilient modulus. Figure 8.10 presents the influence of the saturation condition upon resilient modulus ratio (MMR). It can be observed that the effect of water on the asphalt paving mixtures decreased as the amount of baghouse fines/asphalt cement ratio decreased or asphalt cement content increased.

The test results of resilient modulus are tabulated in Appendix C-6. Test results include data on each replicate test.

Table 8.7 ANOVA Results for the Resilient Modulus (Design No. 4)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	2	54.14	27.07	2.53	0.1339
P	2	483.85	241.93	22.65	0.0003
BP	4	22.99	5.75	0.54	0.7118
S(BP)	9	96.11	10.68		
W	2	9141.80	4570.90	874.60	0.0001
BW	4	28.11	7.03	1.34	0.2920
PW	4	225.22	56.31	10.77	0.0001
BPW	8	13.32	1.67	0.32	0.9485
S(BP)W	18	94.07	5.23		
T	2	9722.30	4861.15	1416.04	0.0001
BT	4	68.21	17.05	4.97	0.0071
PT	4	77.51	19.38	5.64	0.0040
BPT	8	27.04	3.38	0.98	0.4794
S(BP)T	18	136.35	7.58	2.21	0.0511
WT	2	85.31	42.66	12.43	0.0004
BWT	4	7.09	1.77	0.52	0.7249
PWT	4	14.74	3.68	1.07	0.3987
BPWT	8	6.29	0.79	0.23	0.9803
S(BP)WT	18	61.79	3.43		
	291				





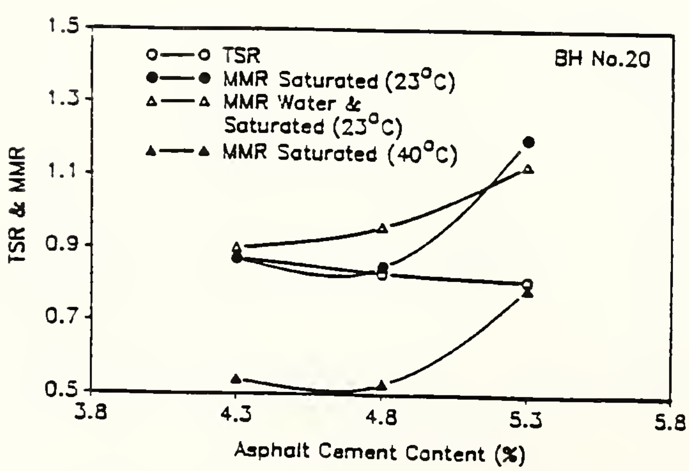


Figure 8.10 Resilient Modulus Ratio and Tensile Strength Ratio o
Asphalt Paving Mixtures (Design No. 4)

8.3.3 Indirect Tensile Strength

Indirect tensile strength and failure tensile strain were measured on asphalt paving mixtures containing different asphalt cement content (baghouse fines/asphalt cement ratio) under dry and saturated conditions. ANOVAs were performed on the obtained data using the same statistical model used as previously in section 8.2.4, with the exception that the oven effect terms were replaced by water saturation. The ANOVA results are represented in Table 8.8 and Table 8.9. Figure 8.11 depicts the indirect tensile strength under different conditions of water saturation. It can be observed that the water sensitivity test significantly reduced the indirect tensile strength of the asphalt paving mixtures. However, the kinds of baghouse fines, asphalt cement content (baghouse fine/asphalt cement ratio) and their interaction were not significant on the indirect tensile strength and failure tensile strain of apshalt paving mixtures. The indirect tensile strength ratio (TSR) for stage 3 exposure was presented in Figure 8.10. It can be noted that the indirect tensile strength ratio was greater than 75%. The effect of water on the asphalt paving mixtures decreased as the amount of baghouse fines/asphalt cement content decreased or asphalt cement content increased. This trend was the same as for the indirect resilient modulus test. It can also be noted that the water sensitivity test caused drastic reductions in the indirect tensile strength of unaged asphalt paving mixtures. The indirect tensile strength ratio of unaged asphalt paving specimens was only about 80% of the asphalt plant simulated specimens.

Table 8.8 ANOVA Results for Indirect Tensile Strength (Design No. 4)

Source of Variation	df	SS	MS	F	PR>F
B	2	207.76	103.88	0.05	0.9528
P	2	1098.45	549.23	0.26	0.7762
BP	4	6324.24	1581.06	0.74	0.5758
W	1	31597.71	31597.71	14.73	0.0008
BW	2	1905.57	952.79	0.44	0.6465
PW	2	1314.01	657.01	0.31	0.7390
BPW	4	1062.54	265.64	0.12	0.9725
ϵ	24	51473.33	2414.72		
	41	94983.62			

Table 8.9 ANOVA Results for Failure Tensile Strain (Design No. 4)

Source of Variation	df	SS	MS	F	PR>F
B	2	0.209	0.105	0.10	0.9034
P	2	2.715	1.358	1.32	0.2847
BP	4	3.881	0.970	0.95	0.4543
W	1	4.600	4.600	4.49	0.0447
BW	2	1.415	0.708	0.69	0.5112
PW	2	1.411	0.706	0.69	0.5122
BPW	4	0.615	0.154	0.15	0.9612
ϵ	24	24.598	1.025		
	41	39.444			

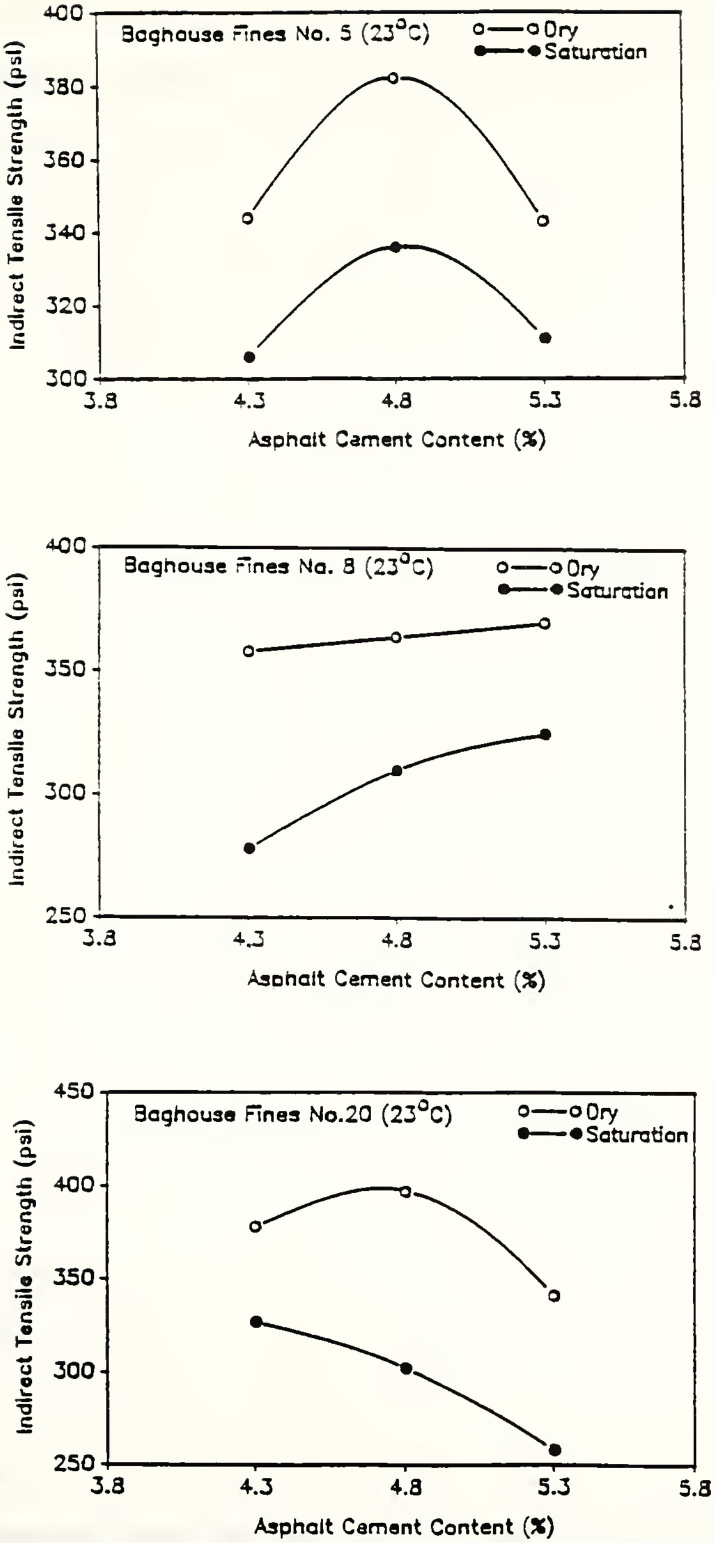


Figure 8.11 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Baghouse Fines/Asphalt Cement Content (BH + AC = Constant; Design No. 4)

8.3.4 Summary of Results

1. The indirect tensile strength of asphalt paving mixtures appears to be quite sensitive to water damage. Since Marshall test specimens are easily fabricated by most national laboratories, the splitting indirect tensile test lends itself quite well to evaluating moisture sensitivity.
2. This test program indicated that the use of age hardening improved the resistance of asphalt paving mixtures to damage by water saturation.
3. The resilient modulus test performed on specimens after saturation can give confusing results at room test temperatures and high asphalt cement content (low baghouse fines/asphalt cement ratio).
4. The addition of baghouse fines to the asphalt paving mixtures decreased the effect of water sensitivity with an increasing asphalt cement content or decreasing baghouse fines/asphalt cement ratio.

8.4 Densification

Asphalt pavements with high initial air void levels at time of construction will densify further under traffic loads. This reduction in air voids is typically called traffic densification. The change in air voids under traffic load can be evaluated in the laboratory by using different compactive efforts and methods. The Texas Gyratory and the U.S. Corps of Engineers Gyratory Testing

Machine (GTM) demonstrated a slight superiority in its ability to produce specimens with material properties that simulate field conditions (32). ASTM D3387 and ASTM D4013 are standardized procedures for compacting test specimens. The gyratory testing machine is a versatile piece of equipment that simulates traffic densification and can be used to prepare and compact asphalt paving mixtures in the laboratory. In this test program, the GTM was set at a 1 degree angle, 200 psi ram pressure, and 20 psi oil-filled roller pressure to compact the specimens that had been placed in a 140°F oven for 24 hrs. The traffic densification simulation tests were performed up to a total of 300 revolutions.

This section presents the results of Design No. 5 which dealt with the behavior of asphalt paving mixtures having different kinds of baghouse fines and asphalt contents. The independent variables included the kinds of baghouse fines, the asphalt content, the compactive effort, and the testing temperature. Gyratory parameters were obtained during the compaction process. The properties of asphalt paving mixture measured at various temperatures were resilient modulus, the indirect tensile strength, and the failure tensile strain. The general laboratory procedures described in Chapter 4 were used to prepare and to test the asphalt paving mixtures.

8.4.1 Gyratory Parameters

The gyratory indices for the asphalt paving mixtures in Design No. 5 are presented in Figure 8.12. ANOVAs were performed on the

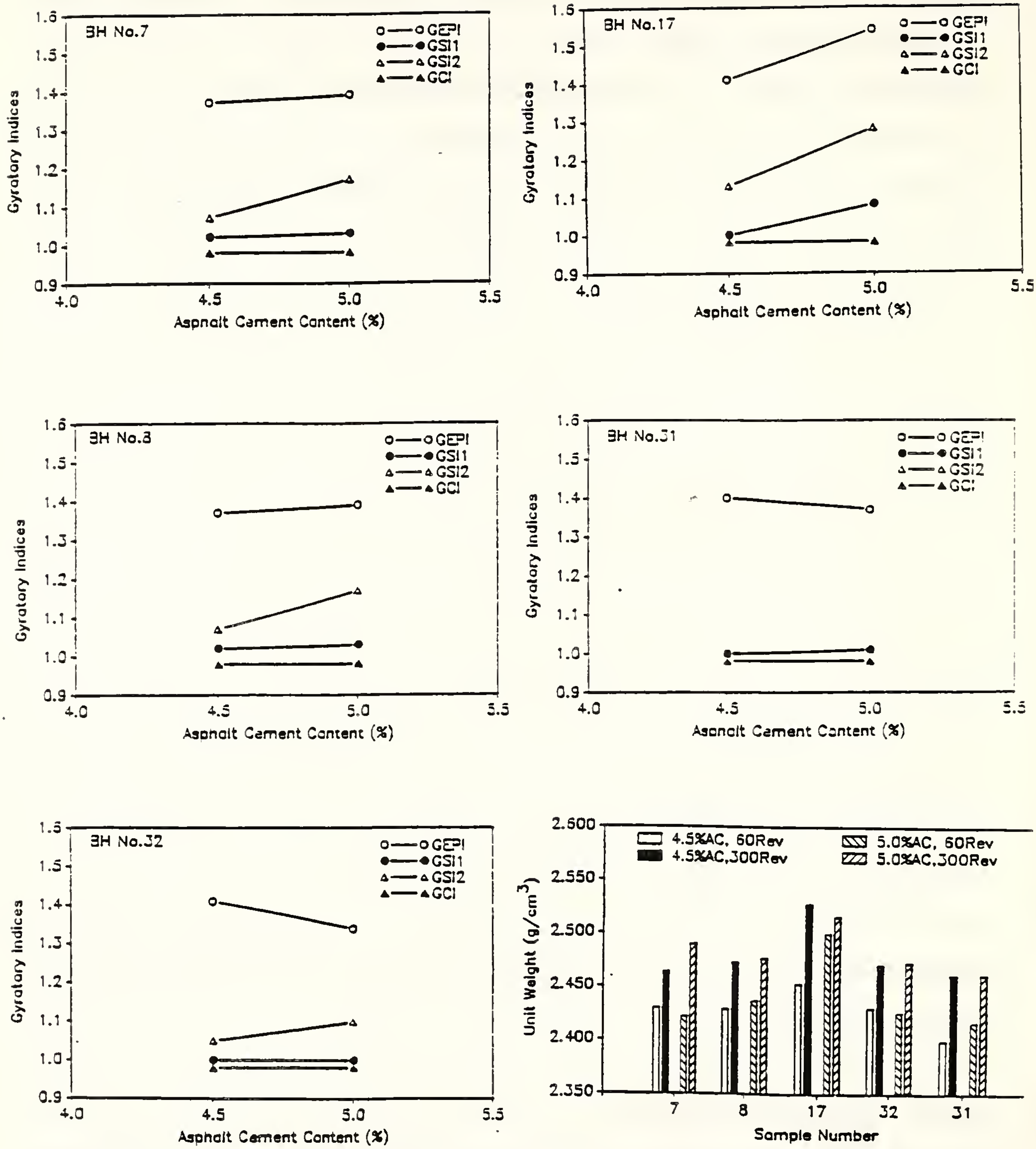


Figure 8.12 Gyratory Indices of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 5)

Table 8.10 ANOVA Results for Gyratory Parameters (Design No. 5)

Source of Variation	GEPI	Response GSI1	Variable GSI2	GCI	rd
B	S.*	S.	S.	N.S.	S.
P	N.S.	S.	S.	N.S.	S.
D	S.*	N.S.	N.S.	N.S.	S.
BP	N.S.	S.	N.S.	N.S.	N.S.
BD	N.S.	N.S.	N.S.	N.S.	S.
PD	S.*	N.S.	N.S.	N.S.	N.S.
BPD	N.S.	N.S.	N.S.	N.S.	S.

S. = significant at $\alpha = 0.05$, N.S. = not significant at $\alpha = 0.05$,

S.* = significant at $\alpha = 0.10$

obtained data using the statistical model which was used in section 8.2. The ANOVA results are presented in Table 8.10. It can be noted that the gyratory compactibility indices (GCI) were insensitive to the kinds of baghouse fines and asphalt content. The gyratory stability index (GSI) increased with increasing asphalt cement content, except the No. 31 samples which contained no baghouse fines or mineral fillers. The main factors (type of baghouse fines, asphalt content, and densification) significantly affected the unit weight of asphalt paving mixtures. The interactions BD and BPD also were significant. The higher compactive efforts and asphalt contents resulted in higher unit weights of asphalt paving mixtures.

8.4.2 Resilient Modulus

ANOVA were performed on resilient modulus data using the following statistical model:

$$\begin{aligned} Y_{ijklm} = \; & \mu + B_i + P_j + BP_{ij} + O_k + BO_{ik} + PO_{jk} + BPO_{ijk} + \\ & S(BPO)_{(ijk)l} + \delta_{(ijk)l} + T_m + BT_{im} + PT_{jm} + OT_{km} + BOT_{ikm} + \\ & POT_{jkm} + BPOT_{ijkm} + S(BPO)T_{(ijk)lm} + \epsilon_{ijklm} \text{------} 8.5 \end{aligned}$$

The model is similar to the linear model described in the previous section 7.2 with the exception that the compactive effort terms were replaced by the densification effort. The results of ANOVA are presented in Table 8.11. The resilient modulus values of asphalt paving mixtures in design No. 5 are present in Figure

Table 8.11 ANOVA Results for Resilient Modulus (Design 5)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	4	79.61	19.92	3.37	0.0289
P	1	6.24	6.24	1.06	0.3156
D	1	68.40	68.40	11.60	0.0028
BP	4	49.84	12.46	2.11	0.1170
BD	4	17.34	4.34	0.73	0.5789
PD	1	22.12	22.12	3.75	0.0670
BPD	4	26.10	6.53	1.11	0.3810
S(BPD)	20	117.94	5.90		
T	2	21908.17	10954.09	4656.90	0.0001
BT	8	76.04	9.51	4.04	0.0014
PT	2	8.25	4.13	1.75	0.1862
DT	2	289.97	144.99	61.64	0.0001
BPT	8	47.66	5.96	2.53	0.0248
BDT	8	50.11	6.26	2.66	0.0192
PDT	2	12.45	6.23	2.65	0.0833
BPDT	8	14.94	1.87	0.79	0.6110
S(BPD)T	40	94.09	2.35		
ϵ	119				

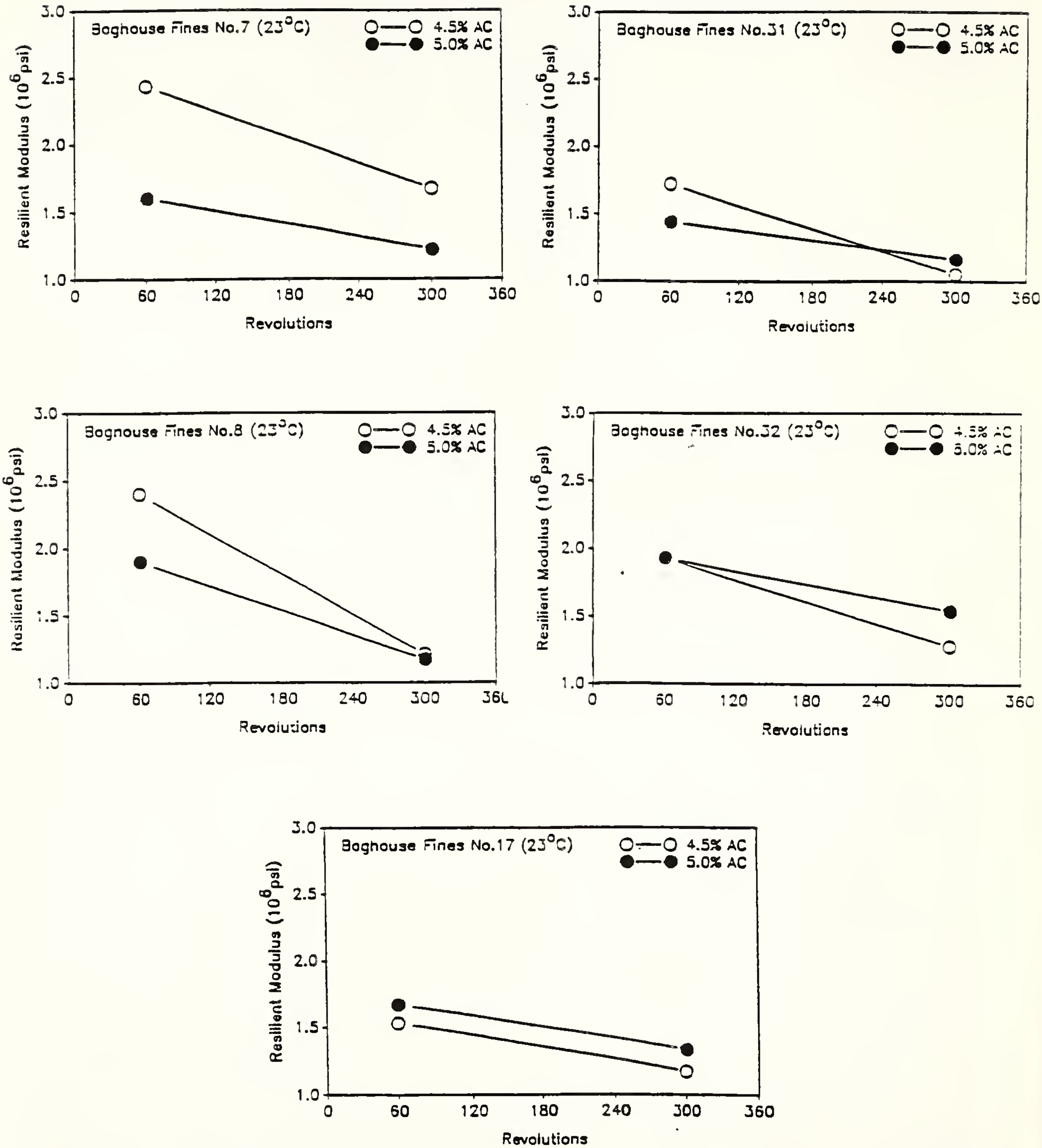


Figure 8.13 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 5) (Continue)

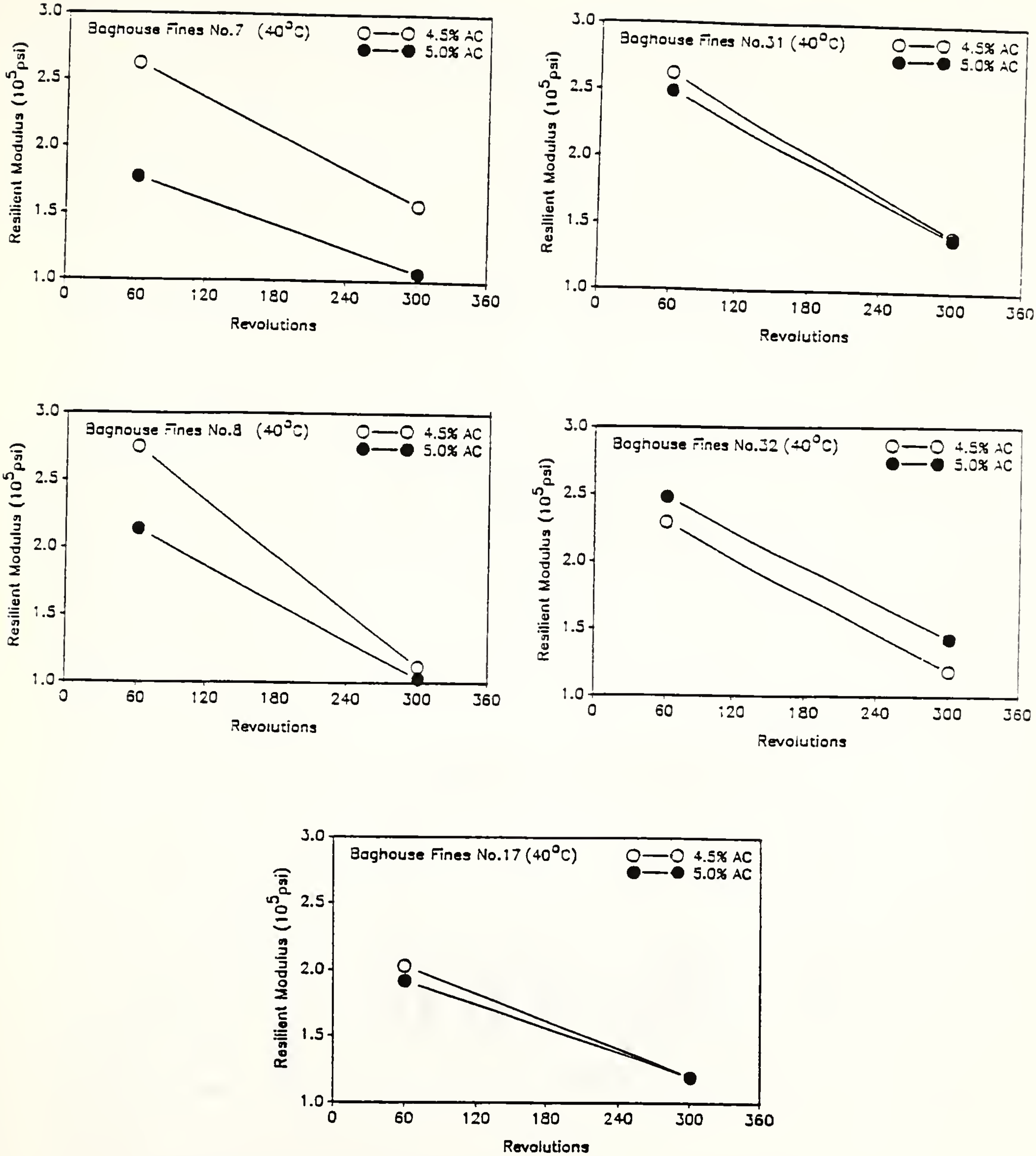
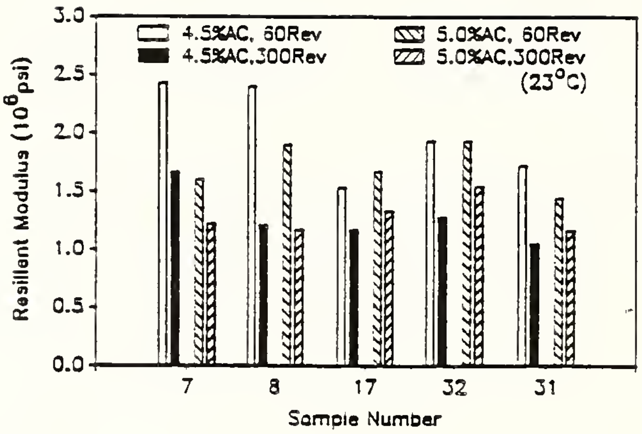


Figure 8.13 Resilient Modulus of Asphalt Paving Mixtures Containing Baghouse Fines (Design No. 5)



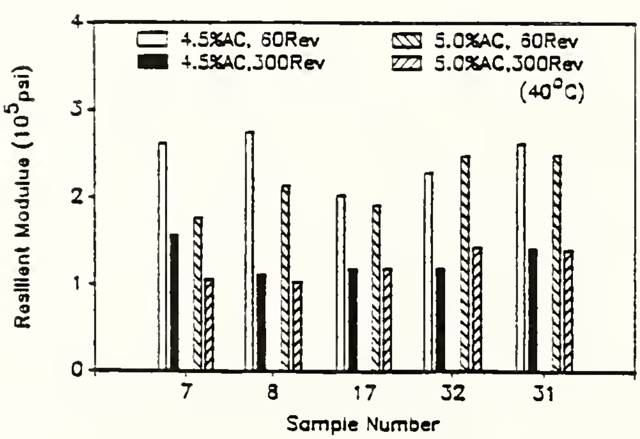


Figure 8.14 Resilient Modulus of Asphalt Paving Mixtures Containing Different Types of Baghouse Fines (Design No. 5)

8.13. It can be observed that the resilient modulus at room temperature and the higher temperature decreased significantly as compactive effort increased. At the lower temperature this phenomenon was not observed. Figure 8.14 represents the comparison of resilient modulus between different baghouse fines.

8.4.3 Indirect Tensile Strength

Indirect tensile strength and failure tensile strain measurements were collected on asphalt paving mixtures containing different kinds of baghouse fines and hydrated lime. The asphalt content was controlled near the optimum level. ANOVA was performed on the obtained data using the same statistical model as in the previous section 8.2.4. The test results as tabulated in Appendix C-10 were analyzed as results of a factorial experiment. The ANOVA results are displayed in Table 8.12. The effects of densification and asphalt content were not significantly different. The differences among baghouse fines were very significant. Figure 8.15 depicts the indirect tensile strength of asphalt paving mixtures under different compactive effort. The increase in indirect tensile strength of the asphalt paving mixtures is more pronounced with greater compactive effort (densification) at higher testing temperatures. Figure 8.16 depicts the indirect tensile strength as affected by the different baghouse fines and mineral fillers. The indirect tensile strength of sample No. 31, which had no added baghouse fines or mineral fillers, is the lowest in this series.

Table 8.12(a) ANOVA Results for Indirect Tensile Strength (Design 5)

Source of Variation	df	SS	MS	F	PR>F
B	4	31438.56	7859.64	13.14	0.0002
P	1	4.67	4.67	0.01	0.9309
D	1	34.99	34.99	0.06	0.8126
BP	4	3486.79	871.70	1.46	0.2709
BD	4	4149.63	1037.41	1.73	0.2023
PD	1	161.04	161.04	0.27	0.6125
BPD	4	2853.74	713.44	1.19	0.3597
T	1	3041426.66	3041426.66	5086.40	0.0001
BT	4	24356.61	6089.15	10.18	0.0006
PT	1	123.53	123.53	0.21	0.6570
DT	1	1262.74	1262.74	2.11	0.1697
ϵ	13	7773.39	597.95		
	39	3264950.62			

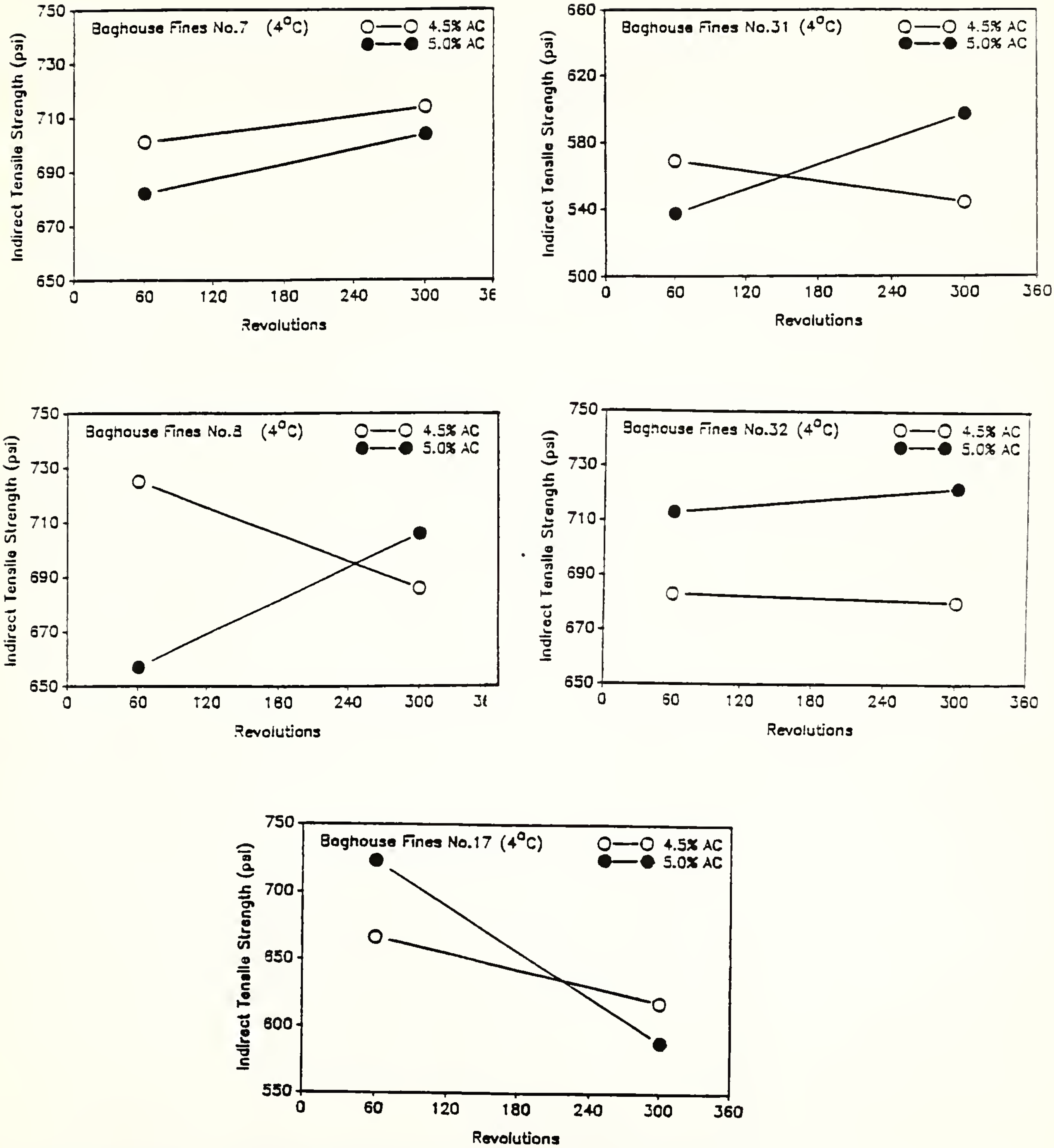


Figure 8.15 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Different Baghouse Fines (Design No. 5) (Continue)

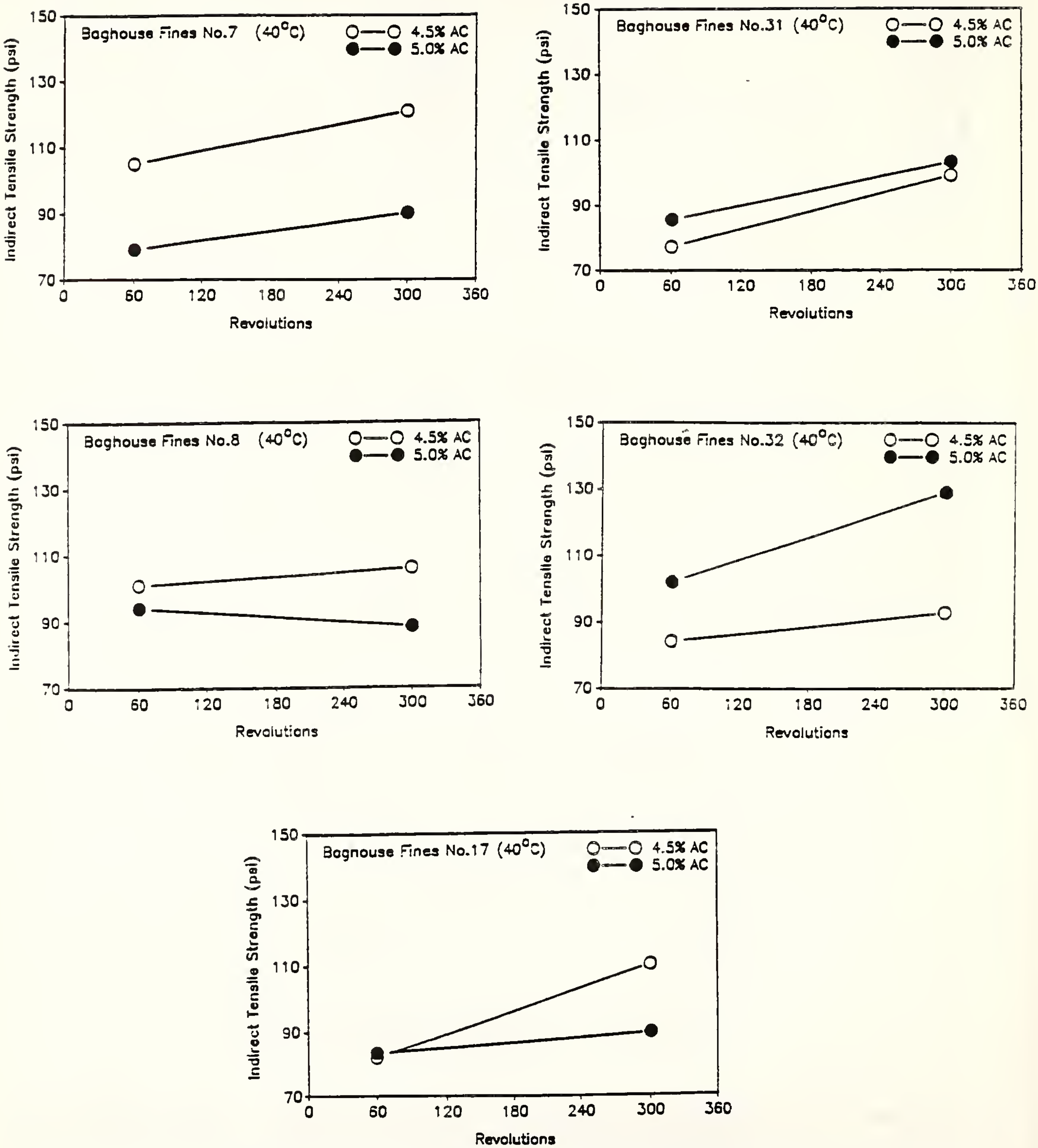
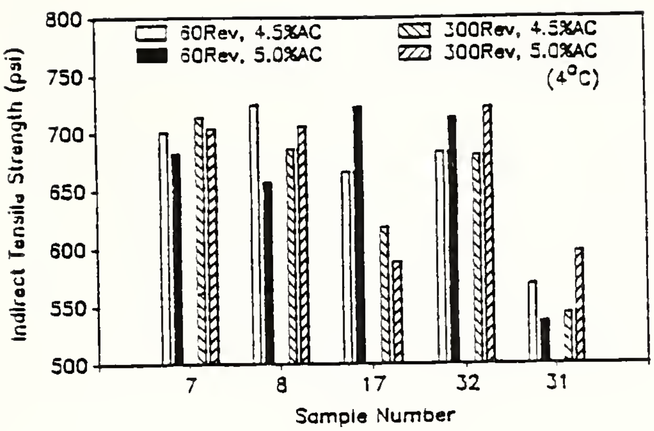


Figure 8.15 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Different Baghouse Fines (Design No. 5)



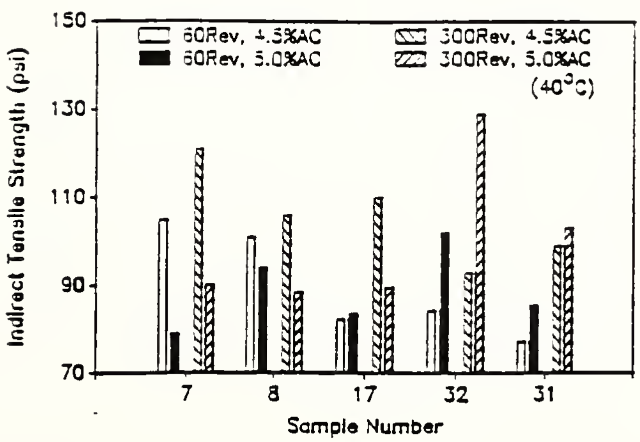


Figure 8.16 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Different Types of Baghouse Fines (Design No. 5)

8.4.4 Summary of Results

1. The kind of baghouse fines and asphalt cement content affected the gyratory stability index and unit weight of asphalt paving mixtures. In addition, densification was significant on the unit weight of asphalt paving mixture.
2. The resilient modulus of asphalt paving mixtures decreased significantly as compactive effort increased at room temperature and at the higher testing temperature.
3. The indirect tensile strength of asphalt paving mixtures increased significantly as compactive effort increased at the higher testing temperature.

CHAPTER 9

COMPARISON OF ASPHALT PAVING MIXTURES WITH BAGHOUSE FINES AND MINERAL FILLERS

9.1 Introduction

The particle size distribution, particle shape, surface area, surface texture, and minerological composition of baghouse fines and mineral fillers all affect the properties of asphalt paving mixtures. It is important to know the source of baghouse fines and the characteristics of commercial mineral fillers being used, and to compare their properties to those used for mixture design. The objectives of this substudy on the evaluation of selected mineral fillers and baghouse fines for use in the asphalt plant are summarized as follows:

1. The gyratory testing machine will be used to evaluate the stability and compactibility of asphalt paving mixtures containing baghouse fines and mineral fillers collected by the INDOT personnel.
2. Indirect tensile and resilient modulus tests will be performed to determine the potentially beneficial effects of baghouse fines and mineral fillers.
3. The influence of gradation of baghouse fines with a constant mineralogical character upon the physical properties of asphalt paving mixtures will be evaluated.
4. Statistical analysis will be conducted to test the significance and to find the relationship among test parameters.

This chapter presents the results of Design 6 and 7, which dealt with the behavior of asphalt paving mixtures with the addition of baghouse fines or mineral fillers. In Design No. 6, four mineral fillers (namely, hydrated lime, silica filler, fly ash, and silica fume), one baghouse fines, and one zero fines were used as the additives to the asphalt paving mixtures. In Design 7, two mineral fillers, two baghouse fines having a coarse and fine gradation and one zero fines were used as the additives to the asphalt paving mixtures.

The general laboratory test procedures that were followed had been previous presented in Chapter 4.

9.2. Results of Experimental Design No. 6

9.2.1 Gyratory Parameters

ANOVAs were performed on the obtained data (Appendix D-1) using the following model:

$$Y_{ijk} = \mu + B_i + P_j + BP_{ij} + \epsilon_{ijk} \qquad 9.1$$

This is a completely randomized factorial design. The terms in the model are as defined in Chapter 7, Section 7.2. The ANOVA results are presented in Table 9.1.

Figure 9.1 depicts the gyratory indices of Design No. 6. It can be noted that all the gyratory indices were significant to the change of baghouse fines and mineral fillers content. The fillers and fines content increased from 3% to 6%. The gyratory indices increased in different amounts depending on the types of fines and

Table 9.1 ANOVA Results for Gyratory Parameters (Design No. 6)

Source of Variation	Response of Variable GEPI	GSII	GSI2	GCI	rd
B	S.	S.	S.	S.	S.
P	S.	S.	S.	S.	S.
P+B	N.S.	S.	S.	S.	S.

S. = significant at $\alpha = 0.05$, N.S. = not significant at $\alpha = 0.05$

S.* = significant at $\alpha = 0.10$

Table 9.2 ANOVA Results for Resilient Modulus (Design No. 6)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	4	106.63	26.66	4.58	0.0087
P	1	6.13	6.13	1.05	0.3174
BP	4	14.34	3.59	0.62	0.6565
S(BP)	20	116.49	5.83		
T	2	1640.74	820.37	3288.37	0.0001
BT	8	8.62	1.08	4.32	0.0008
PT	2	2.07	1.04	4.15	0.0230
BPT	8	12.11	1.51	6.07	0.0001
S(BP)T	40	9.98	0.250		
	89	1697.87			

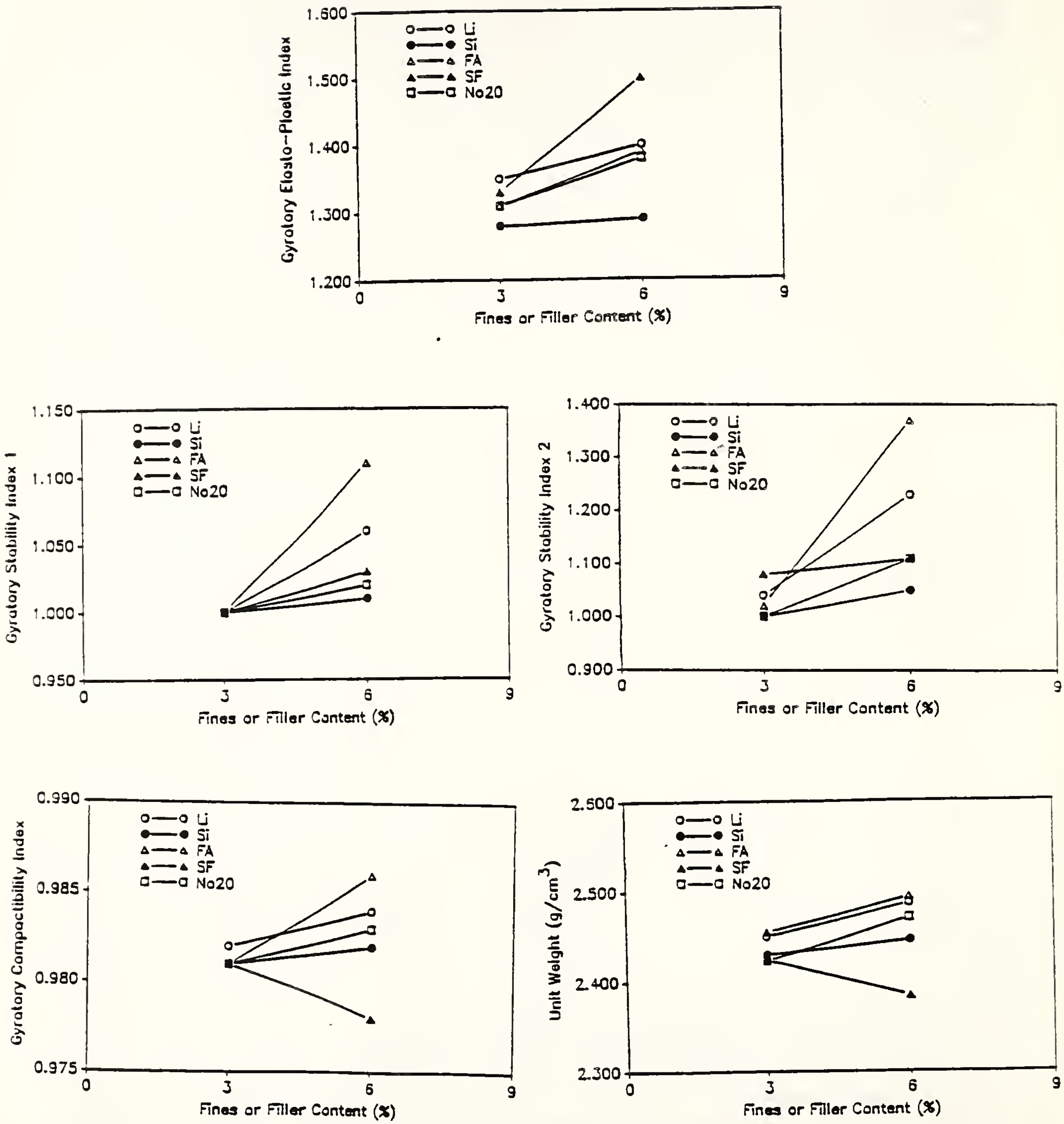


Figure 9.1 Gyratory Parameters of Asphalt Paving Mixtures Containing Mineral Fillers (Design No. 6)

fillers, except for the gyratory compactibility indices (GCI) when silica fume was used.

9.2.2 Resilient Modulus (Design No. 6)

The resilient modulus of asphalt paving mixtures in Design No. 6 are presented in Figure 9.2 and Appendix D-2. ANOVAs were performed on the resilient modulus data using the following mathematical model:

$$Y_{ijkl} = \mu+P_i+B_j+PB_{ij}+S(PB)_{(ij)k}+\delta_{ijk}+T_l+PT_{il}+PT_{jl}+PBT_{ijl}+S(PB)_{(ij)kl}+\epsilon_{ijkl} \quad 9.2$$

The model is similar to the general model described in the previous Chapter 7, Section 7.4.2. The results of ANOVA are presented in Table 9.2.

The ANOVA results and Figure 9.2 indicate that the effects of fines or fillers content (P) were not significant, but the effects of different kinds of fines or filler were significant. The resilient modulus of asphalt paving mixtures with the addition of silica fume seem higher than other fines or fillers when tested at temperatures above room temperature. The effects of fines or fillers content on resilient modulus were distinct between silica fume and other fines or fillers. When silica fume was used as the additive, the resilient modulus of asphalt paving mixtures generally increased as the fillers content increased. This was due to the stiffening of the asphalt paving mixtures caused by the addition of the silica fume.

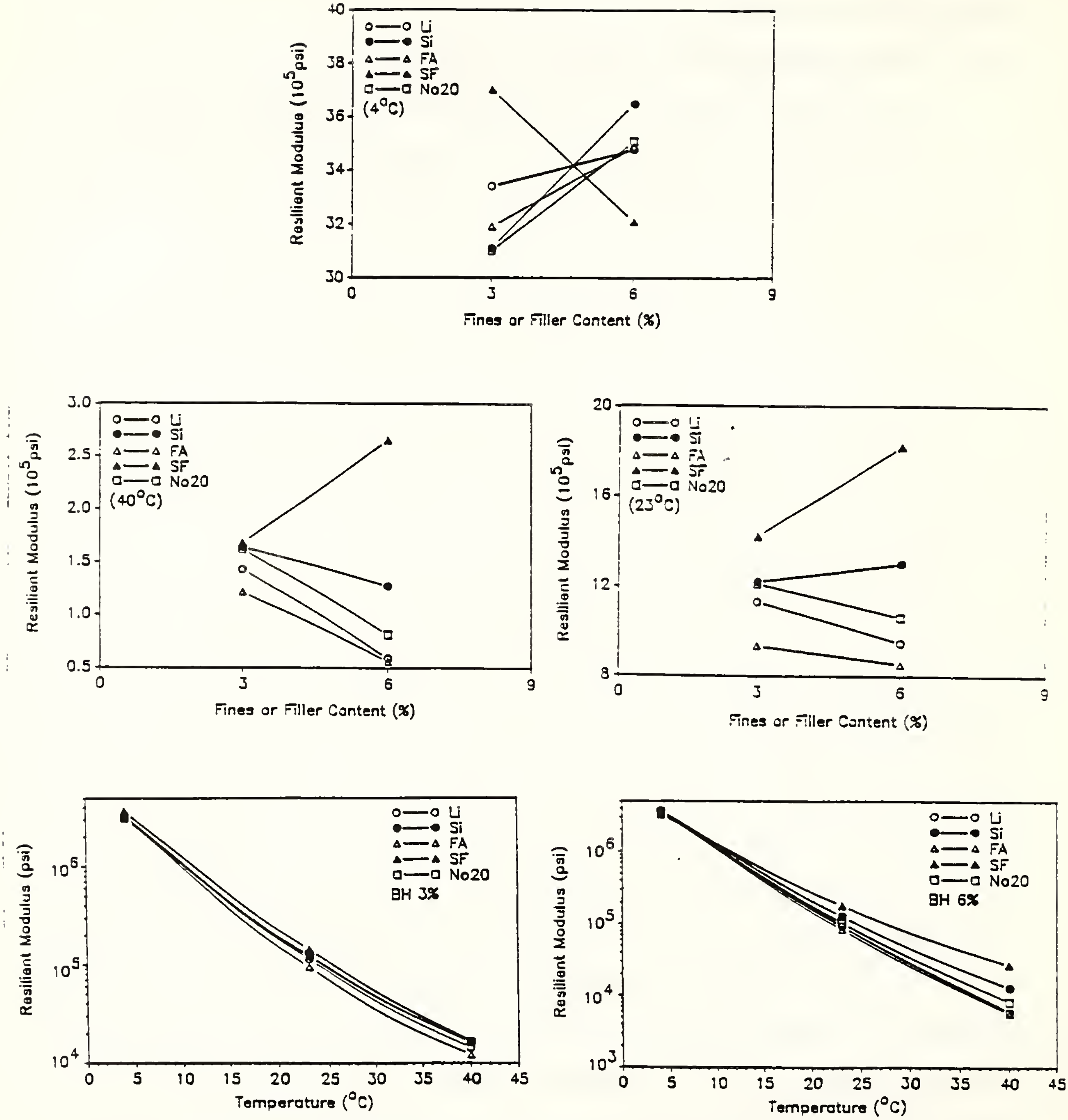


Figure 9.2 Resilient Modulus of Asphalt Paving Mixtures Containing Mineral Fillers (Design No. 6)

9.2.3 Indirect Tensile Strength

The indirect tensile strengths and failure tensile strain measured at different temperatures were analyzed with the aid of ANOVA statistical method using the following model:

$$Y_{ijkl} = \mu+P_i+B_j+T_k+PB_{ij}+PT_{ik}+BT_{jk}+PBT_{ijk}+\epsilon_{ijk} \qquad 9.3$$

This is a completely randomized design. The ANOVA results and test data are presented in Table 9.3 and Appendix D.3. The influence of fines and fillers on the indirect tensile strength of asphalt paving mixtures was similar to the resilient modulus that was reported in Section 9.2.2. The indirect tensile strength increased as filler content increased at higher temperature. The indirect tensile strengths decreased as the filler content increased at lower temperatures.

9.3 Effect of Baghouse Fines or Mineral Fillers Gradation on Asphalt Paving Mixtures

The effects of fines or fillers gradation, kinds of fines or fillers, and content of fines or fillers on the behavior of asphalt paving mixtures were evaluated. Two fines or fillers gradations (coarse and fine) were used in the study.

9.3.1 Gyratory Parameters

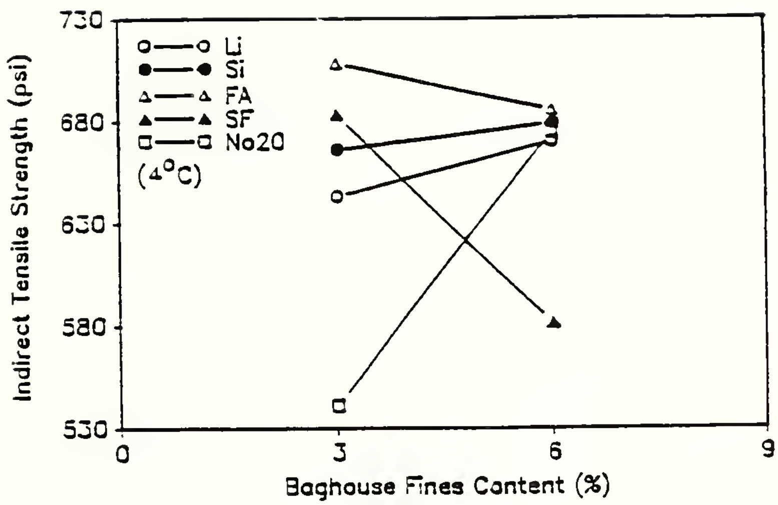
The main factors (gradation, fillers or fines content, and types of fillers or fines) significantly affected the gyratory elasto-plastic index, gyratory stability index and unit weights of

Table 9.3 ANOVA Results for Indirect Tensile Strength (Design No. 6) (continuous)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	4	3884.89	971.22	0.42	0.7893
P	1	6.05	6.05	0.00	0.9617
BP	4	5947.92	1486.98	0.64	0.6604
T	1	1612211.33	1612211.33	697.09	0.0001
BT	4	9553.49	2388.37	1.03	0.4879
PT	1	361.25	361.25	0.16	0.7129
ϵ	4	9251.12	2312.78		
	19	1641216.05			

Table 9.3 ANOVA Results for Failure Tensile Strain (Design No. 6)

Source of Variation	df	SS	MS	F	PR>F
B	4	1.600	0.400	1.05	0.4827
P	1	0.242	0.242	0.63	0.4701
BP	4	0.868	0.167	0.57	0.7014
T	1	1.250	1.250	3.27	0.1447
BT	4	0.700	0.175	0.46	0.7659
PT	1	0.032	0.032	0.08	0.7866
ϵ	4	1.528	0.382		
	19	6.220			



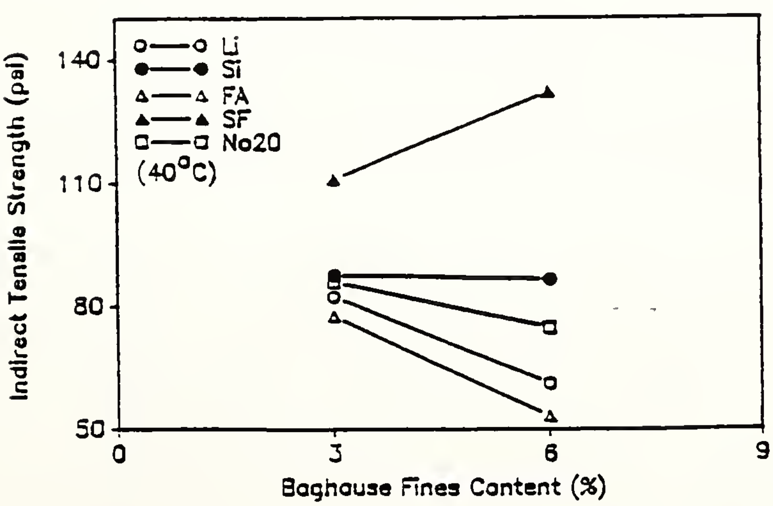


Figure 9.3 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Mineral Fillers (Design No. 6)

asphalt paving mixtures. In addition, the fillers or fines content also affected the gyratory compactibility index. The two factor interaction (PB) was significant. The ANOVA results and test results are presented in Table 9.4 and Appendix D-4.

Figure 9.4 depicts the relationship between the gyratory indices and the gradation of fines or fillers. It is apparent that the higher the fines or filler content in the asphalt paving mixtures the higher the GEPI, GSI, and GCI values. The addition of the fine gradation of baghouse fines and fillers to the asphalt paving mixtures resulted in higher GEPI, GSI, and GCI values except for Sample No. 20 with added 6% fines.

9.3.2 Resilient Modulus (Design No. 7)

Results of the resilient modulus test with respect to the four different kinds of baghouse fines or mineral fillers have been tabulated in Appendix D-5. ANOVAs were performed in the resilient modulus data using the following mathematical model:

$$Y_{ijklm} = \mu + P_i + B_j + G_k + PB_{ij} + PG_{ik} + BG_{jk} + (PBG)_{ijk} + S(PBG)_{(ijk)l} + T_m + PT_{im} + BT_{jm} + GT_{km} + \ldots\ldots + \epsilon_{ijklm} \qquad 9.4$$

The results of ANOVA are presented in Table 9.5, where it may be seen that the main factors (types of fillers or fines, fillers or fines content, testing temperature) significantly affected the resilient modulus of the asphalt paving mixtures. The resilient modulus was insensitive to the changes of gradation of fines or fillers in some mineralogical composition. Figure 9.6 presents the

Table 9.4 ANOVA Results for Gyratory Parameters and rd (Design No. 6)

Source of Variation	Response Variable GEPI	GSI1	GSI2	GCI	rd
B	S.	S.	S.	N.S.	S.
P	S.	S.	S.	S.	S.
BP	S.	S.	N.S.	S.*	S.
F	S.*	S.	N.S.	N.S.	S.
BF	N.S.	N.S.	N.S.	N.S.	S.*
PF	N.S.	N.S.	N.S.	N.S.	S.
BPF	N.S.	S.	N.S.	N.S.	N.S.

S. = significant at $\alpha = 0.05$, N.S. = not significant at $\alpha = 0.05$

S.* = significant at $\alpha = 0.10$

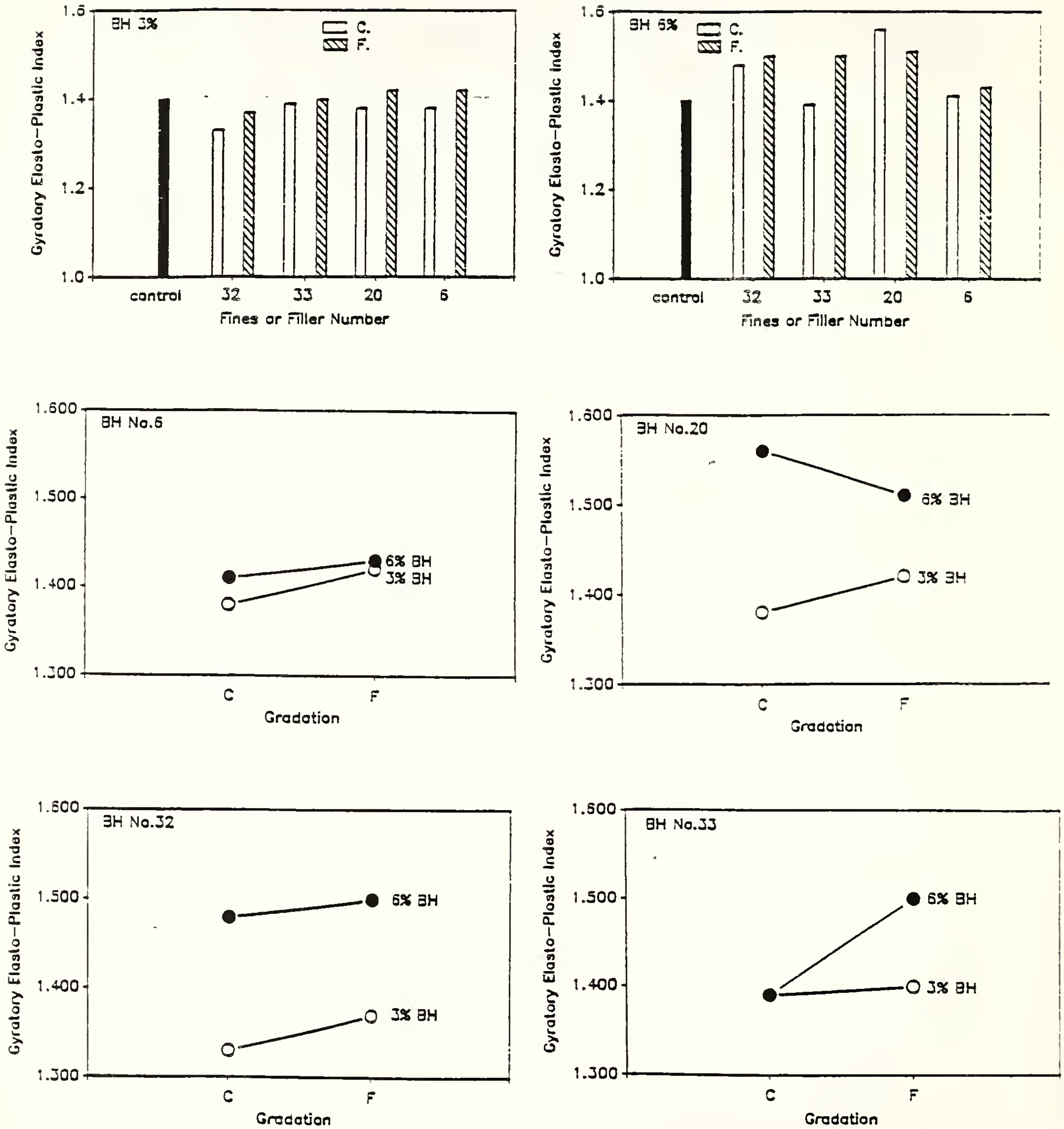


Figure 9.4 Gyratory Indices of Asphalt Paving Mixtures Containing Mineral Fillers or Baghouse Fines (Design No. 7)

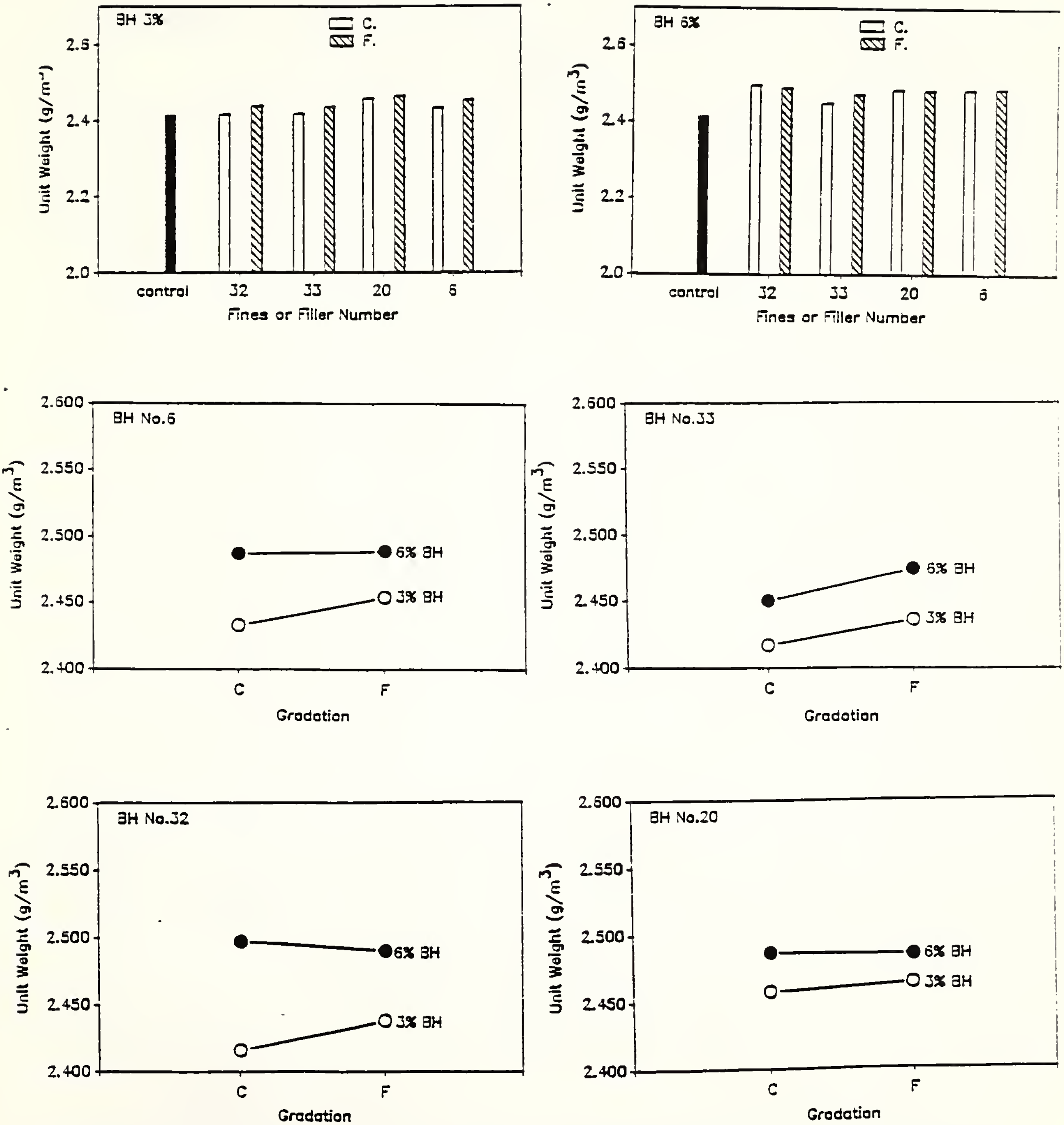


Figure 9.5 Unit Weight of Asphalt Paving Mixtures Containing Mineral Fillers or Baghouse Fines (Design No. 7)

Table 9.5 ANOVA Results for Resilient Modulus (Design No. 7)

Source of Variation	df	SS (10^{10})	MS (10^{10})	F	PR>F
B	3	68.14	22.71	9.96	0.0006
P	1	24.15	24.15	10.59	0.0050
F	1	1.24	1.24	0.55	0.4704
BP	3	19.03	6.34	2.78	0.0747
BF	3	23.08	7.69	3.37	0.0446
PF	1	3.25	3.25	1.42	0.2502
BPF	3	4.42	1.47	0.65	0.5964
S(BPF)	16	36.49	2.28		
T	2	24721.40	1236.07	8348.67	0.0001
BT	6	70.54	1.18	7.94	0.0001
PT	2	11.09	5.55	3.75	0.0345
FT	2	10.30	5.15	3.48	0.0429
BPT	6	9.16	1.53	1.03	0.4234
BFT	6	27.98	4.66	3.15	0.6153
PFT	2	1.78	0.89	0.60	0.3551
BPFT	6	7.74	1.29	0.87	0.5267
S(BPF)T	32	47.38	1.48		
G	18	99.14	5.50		
	113	25186.32			

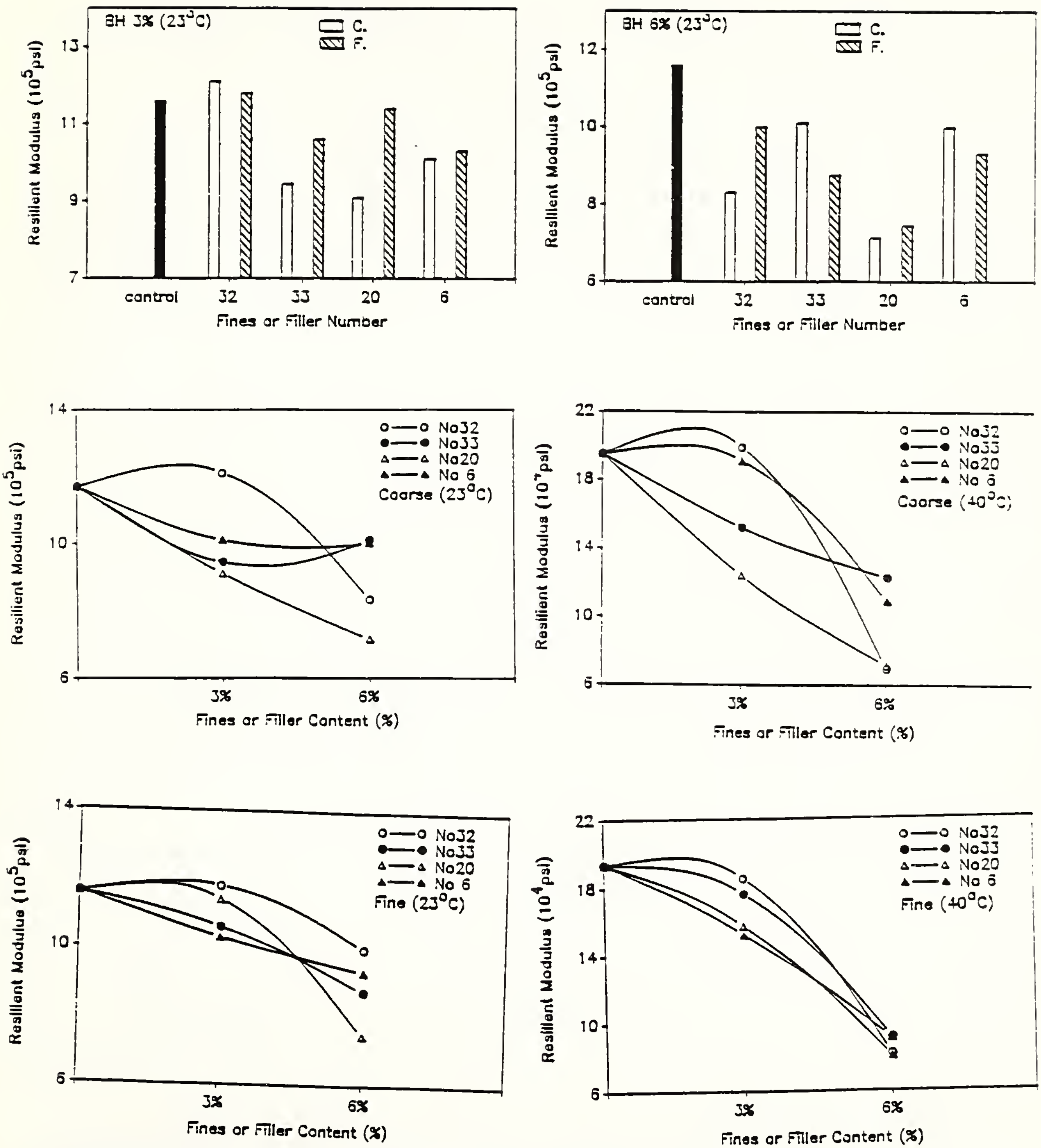


Figure 9.6 Resilient Modulus of Asphalt Paving Mixtures Containing Mineral Fillers or Baghouse Fines (Design No. 7) (Continue)

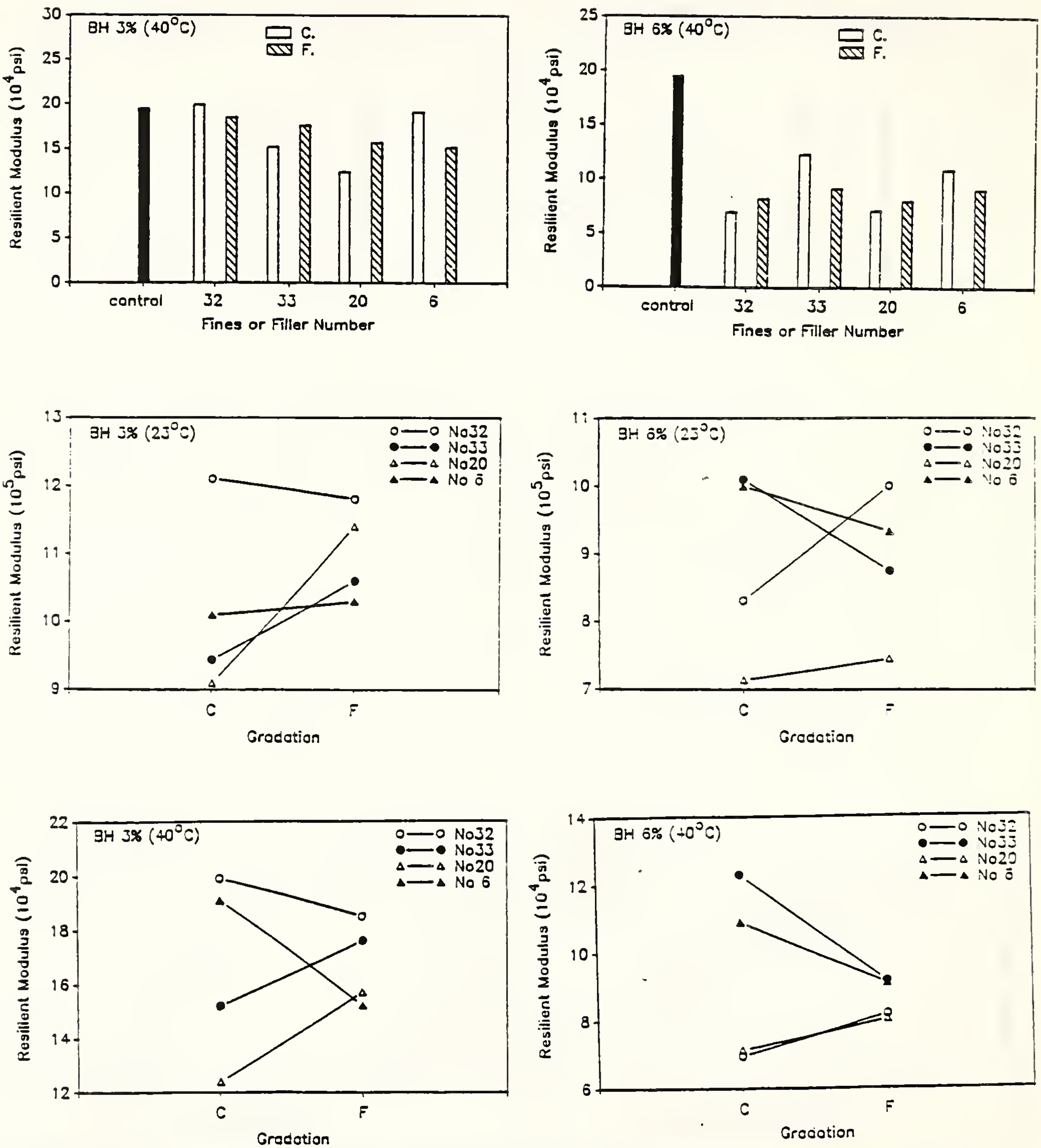


Figure 9.6 Resilient Modulus of Asphalt Paving Mixtures Containing Mineral Fillers or Baghouse Fines (Design No. 7)

resilient modulus as related to gradation of fines or fillers and fines or fillers content for different types of fines or fillers. It is apparent that higher fines or fillers contents in the mixtures result in lower resilient modulus values. The hydrated lime resulted in higher resilient modulus than any of the other fines or fillers at low filler content. The No. 20 samples resulted in lower resilient modulus values than any other fines or fillers at the higher fines content.

9.3.3 Indirect Tensile Strength

Results of the indirect tensile test with respect to the four different kinds of baghouse fines or mineral fillers have been tabulated in Appendix D-6. ANOVAs were performed on the indirect tensile strengths and failure tensile strain using the same model as in Section 9.2.3. The ANOVA results are presented in Table 9.6. Indirect tensile strength were significantly affected by all of the main factors together with some of the two-factor interactions. The temperature showed the most significant effect on the indirect tensile strength as compared to fines or fillers content and types of fines or fillers.

Figure 9.7 presents the indirect tensile strength as related to gradation of fines or fillers and fines or fillers content. It is apparent that for specimens tested at lower temperature, the finer filler or fines in the asphalt paving mixture will result in higher indirect tensile strengths. Besides, the higher fines or fillers contents in the asphalt paving mixtures will result in

Table 9.6 ANOVA for Indirect Tensile Strength
(Design No. 7)

Source of Variation	df	SS	MS	F	PR>F
B	3	1494.17	498.06	7.88	0.0022
P	1	0.11	0.11	0	0.9669
F	1	3602.63	3602.63	56.97	0.0001
T	2	2786945.44	1393472.72	22035.31	0.0001
BP	3	4194.62	1398.21	22.11	0.0001
BF	3	557.36	185.79	2.94	0.0673
BT	6	4661.62	776.94	12.29	0.0001
PF	1	155.97	155.97	2.47	0.1372
PT	1	5943.91	5943.91	93.99	0.0001
FT	2	4700.68	2350.34	37.17	0.0001
ϵ	15	948.57	63.24		
	37	2813205.09			

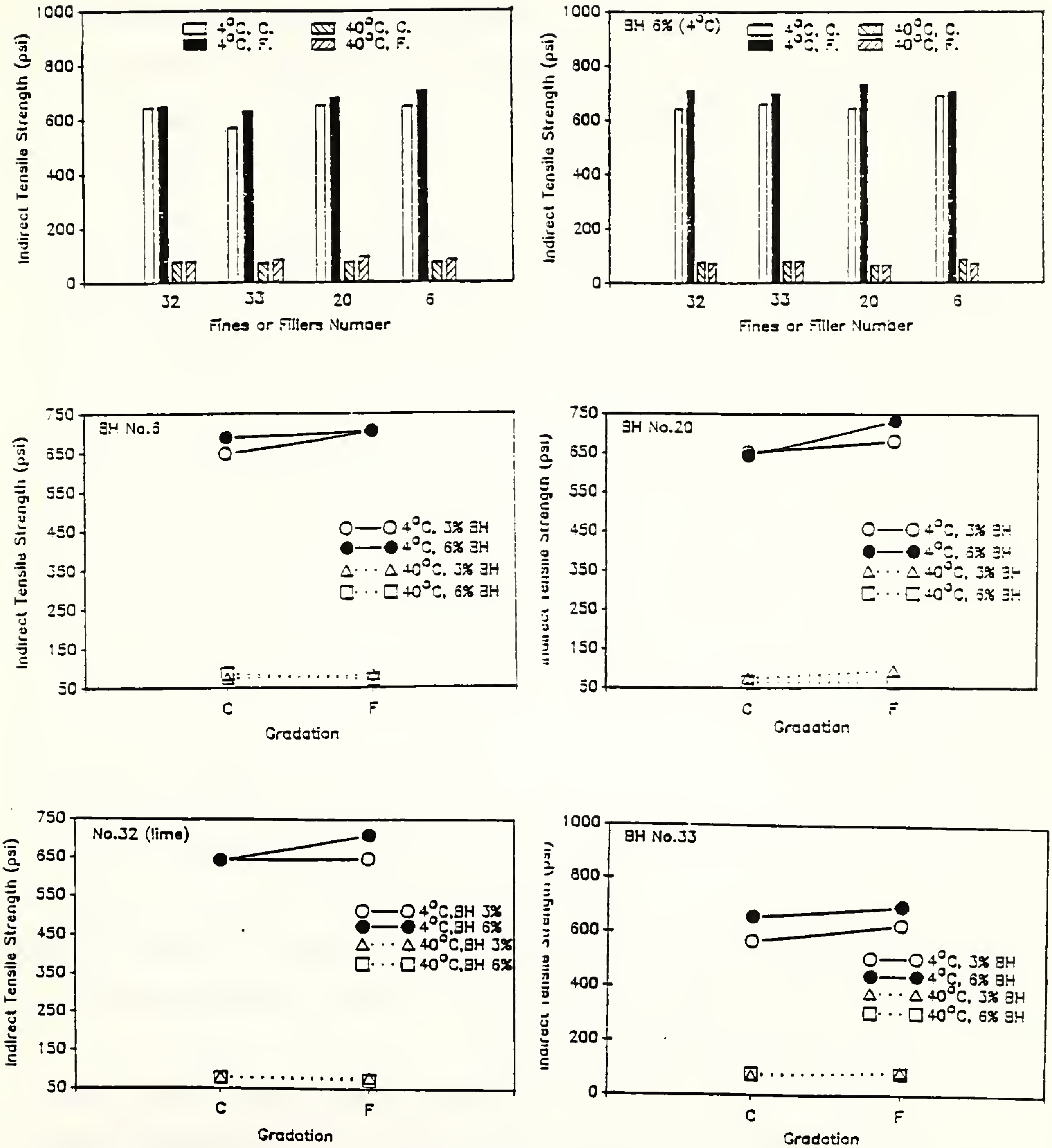


Figure 9.7 Indirect Tensile Strength of Asphalt Paving Mixtures Containing Mineral Fillers or Baghouse Fines (Design No. 7)

higher indirect tensile strengths at lower testing temperatures. However, the phenomenon was opposite at the higher testing temperature; the higher fines or fillers contents caused lower indirect tensile strengths.

9.4 Summary of Results

The analysis and evaluation of the test data in this chapter revealed a number of significant results that pertain to the effect of baghouse fines and mineral fillers with different gradations on the asphalt paving mixtures:

1. The types of baghouse fines or mineral fillers and percent of baghouse fines or mineral fillers significantly affected all the gyratory parameters of asphalt paving mixtures. The percent increases of the gyratory indices varied depending on the types of fines and fillers, with exception of the gyratory compactibility indices of silica fume.
2. The effect of the two and three factor interactions with temperature on the resilient modulus significantly affected the resilient modulus of asphalt paving mixtures.
3. The indirect tensile strengths and resilient modulus values of the asphalt paving mixtures were influenced in similar manner by the baghouse fines and mineral fillers variables that were incorporated in this substudy.
4. Gradation and percent of baghouse fines and mineral fillers significantly affected the unit weight of the asphalt paving mixtures. The higher amount or the finer gradation of

baghouse fines and mineral fillers resulted in higher unit weights of mixtures.

5. The resilient modulus was insensitive to the gradation of baghouse fines or mineral fillers, but the indirect tensile strengths increased significantly with finer baghouse fines or mineral fillers.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

An extensive laboratory study of the asphalt paving mixtures containing baghouse fines has been conducted through seven sets of experimental designs. Fifteen different baghouse fines have been used to produce asphalt mastics. In addition, eight different baghouse fines also have been used as fillers to compare their effects on the mechanical properties of asphalt paving mixtures. It should be noted to indicate that the results obtained herein may be limited to the baghouse fines used and the test conditions applied. Major conclusion from this laboratory study are summarized as follows:

1. The viscosity ratio and softening point may be used to describe the effect of percent bulk volume of baghouse fines on rheological properties of asphalt mastics. The viscosity and softening point increase rapidly when the bulk volume of baghouse fines is between 60 to 80%.
2. Parameters developed from simple dry compaction method to get the void content in baghouse fines, such as B/A, and V_{fB}% appear to be useful for correlation with consistency tests such as penetration, viscosity, ductility, and softening point to indicate the stiffening effects of baghouse fines in asphalt mastics.
3. The gyratory stability index (GSI) and gyratory elasto-plastic

index (GEPI) can be used to determine the effect of baghouse fines on asphalt paving mixtures during the specimen fabrication.

4. The gyratory stability index is very sensitive to baghouse fines content and asphalt cement content. The role of baghouse fines as extenders in asphalt paving mixtures can be demonstrated by the gyratory testing machine.
5. The resilient modulus, indirect tensile strength, and Hveem stability are decreased significantly with higher baghouse fines content. The decrease in resilient modulus with the baghouse fines is caused by the extender action of asphalt cement and baghouse fines interaction.
6. Artificial aging processes to simulate the asphalt plant hardening and in service aging caused an increase in resilient modulus and the indirect tensile strength as well as a reduction in the failure tensile strain values for asphalt paving mixtures. Asphalt paving mixtures containing lower asphalt cement content (high baghouse fines/asphalt cement ratios) tend to age more rapidly than high asphalt cement content (low baghouse fines/asphalt cement ratio).
7. Resilient modulus and indirect tensile strength test parameters were more sensitive to age conditions of asphalt paving mixtures than the Hveem stability test. Those test methods would seem to have some potential for the study of the aging behavior of asphalt paving mixtures.
8. When baghouse fines were added to the asphalt paving mixtures,

the effect of water sensitivity decreased with increasing amount of asphalt cement content or with decreasing amount of baghouse fines/asphalt cement content ratio.

9. Densification generally produces higher indirect tensile strengths for the same asphalt cement content, but it also produces lower resilient modulus values of asphalt paving mixtures. The results from the gyratory densification study may be used to predict field rutting and deformation that occur under traffic.

10. The types of baghouse fines or mineral fillers and amount of baghouse fines or mineral fillers content significantly affected all the gyratory parameters of asphalt paving mixtures. The gyratory indices increased in different amount depending on the types of fines and fillers. The exception was the gyratory compactibility index of silica fume.

11. The resilient modulus value was insensitive to the gradation of baghouse fines or mineral fillers, but the indirect tensile strength increased significantly with finer fines or fillers.

12. The stiffness of asphalt paving mixtures with baghouse fines is sensitive to the grade of asphalt cement, but it is insensitive to the grade of asphalt cement when the asphalt paving mixtures did not include baghouse fines.

10.2 Recommendations

1. The use of HP-GPC analysis for the determination of the amount and the appropriate type of the asphalt mastics

containing baghouse fines should be developed. Studies should be conducted to determine a possible relationship between HP-GPC data and the rheological properties of asphalt mastics.

2. Fatigue properties of asphalt paving mixtures containing different kinds and amounts of baghouse fines which also govern the performance of asphalt pavement should be studied. The relationship between the fatigue properties of the asphalt paving mixtures and the parameters such as the kinds and amounts of baghouse fines, should be established.

3. Different compactive methods have been used by different researchers and engineers to characterize the asphalt paving mixtures. A study should be conducted to relate these different variables to one another using statistical models and an appropriate viscoelastic model for the asphalt paving mixtures.

4. Mechanistic models of structural design are available that can be used to calculate stresses, strains and deflections within the pavement structure. There are other models that can be used to predict fatigue cracking, rutting, or serviceability with traffic and environmental condition.

5. The effect of different grades of asphalt cement on asphalt paving mixtures with baghouse fines should be established.

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APPENDICES

This copy of this report does not include the Appendices listed in the Table of Contents. These are identified as:

Appendix A: Test Data of Design No. 1

Appendix B: Test Data of Design No. 2

Appendix C: Test Data of Design No. 3, No. 4, and No. 5

Appendix D: Test Data of Design No. 6 and No. 7

Appendix E: Test Data of Design No. 8 and No. 9

Appendix F: Test Data of Design No. 10

Appendix G: X-ray Diffraction of Baghouse Fines No. 1-No. 30

Appendix H: Summary of Foster Burr Q-Test Results

Appendix I: ANOVA Results of Design No. 10 and No. 11

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